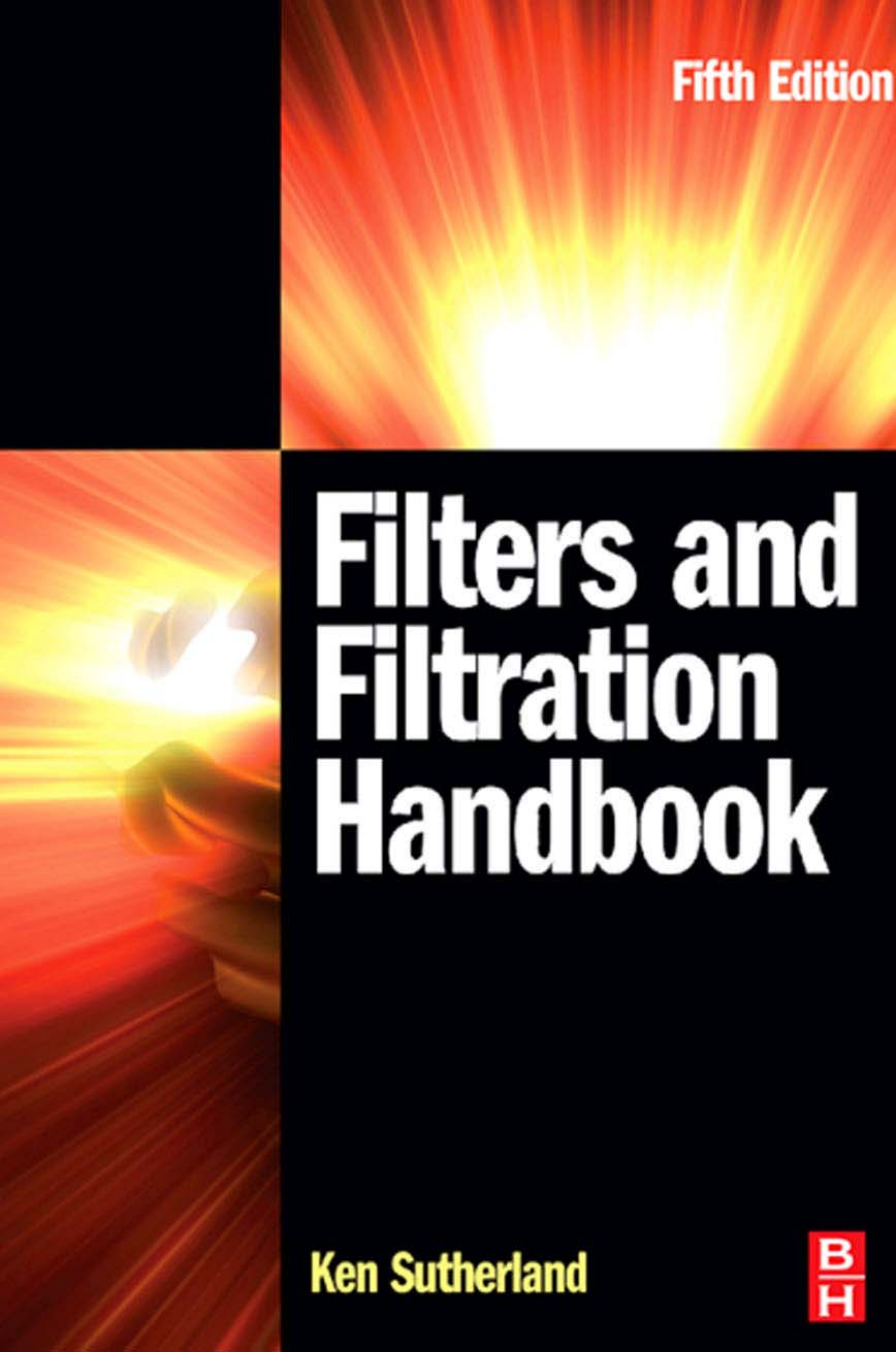

Fifth Edition

Filters and Filtration Handbook

Ken Sutherland

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PREFACE

In the ever-changing world of filtration, one of the constants for many years has been the availability in print of the engineer's reference book, the *Filters and Filtration Handbook*, as, in the words of the Preface to the Fourth Edition, 'a first source of reference and practical guide to filtration and separation products and their applications'.

It did not have too promising a start: I have a copy of the First Edition, and a review of it by 'an authority on solid-liquid separation', which begins: 'At £48, this must be the joke book of the decade, since it really cannot be taken seriously'. Derek's harsh words (for it was, indeed, Derek Purchas who wrote that scathing review) did not prevail, and a change first of author, to Christopher Dickenson, and then of publisher, to Elsevier, has seen it successfully through three more editions, some of which were reprinted.

Which brings us to this Fifth Edition, which may justifiably be considered the Silver Jubilee edition, since it is 25 years since the First Edition was published. With Christopher now retired, the publishers have brought in a new author, tasked with producing a Handbook for the new millennium.

Filtration is a curiously mixed process, with some very old technologies and some very new ones. Much that is old is also unchanged, but not all of it, while some of the new technology would hardly have been noticed for the First Edition. One of the major changes that the quarter-century has brought is the controlling influence of legislation enacted nationally or internationally and covering a wide range of end-use industry sectors, primarily influencing their environmental impact, all the way from extraction of raw materials through to use of the finished product.

Another major driving force for change in the filtration business comes from the end-users, whose increasingly precise businesses – whether in making semiconductors or producing drinking water, in a machine shop or making beer – continually demand finer and finer degrees of filtration. This driver affects the filter medium more than the filter itself, but there is quite a bit of change to be seen in the whole filter unit to accommodate these media changes.

It must be emphasized here that this book is not a textbook on filtration – guidance as to suitable texts will be made in the appropriate place. Nor is it a handbook of process filtration, where the separated solids are as important as the filtered fluid. This handbook deals largely with the removal of solid contaminants from a flow of fluid, liquid or gas, where the degree of contamination is relatively low – but still unacceptable. It thus covers service and process applications where a pure fluid is the required result of the filtration, and the separated solids are unwanted and are usually discarded. Mention is still made of solids recovery filtration, but only sufficiently as to put the rest of the coverage in context. In this same spirit of thorough coverage, mention is made of physical separations by other means, mainly sedimentation.

This, then, is a book about the purification of fluids, primarily by means of filtration. As well as emphasizing this main purpose of the book, the opportunity has been taken in this revised edition to restructure the book in terms of the section order, although most of the topics covered by previous editions are continued in this edition. Information has been updated where necessary, but the book still concentrates on the technology of fluid purification. For a copy of the Filtration and Separation magazine, which also produces an annual Buyer's Guide for subscribed readers, I would refer you to http://www.filtsep.com.

It is hoped that this will be a confident step in the book's progress into its second quarter-century.

Ken Sutherland

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BASIC PRINCIPLES

SECTION CONTENTS

1A. FILTRATION AND SEPARATION

A book entitled *Filters and Filtration Handbook* is clearly stating its purpose in those words, but the primary topic – fluid purification free of contaminants by means of mechanical separation processes – requires a somewhat broader coverage than those words imply. The title of this chapter suggests that broader coverage, even if it is a little confusing, because filtration is one form of separation. The title is, in fact, shorthand for the more cumbersome phrase: 'filtration and other related forms of separation', and has been used in that way for over 40 years, as the title of a leading magazine in the industry proclaims. Throughout this book the term 'filtration' should thus be read as to imply that broader term (unless the context suggests the narrower definition).

So it is perhaps as well to start with some sort of definition of these terms, in the context of this Handbook. *Filtration* specifically, and *separation* generally, refer to the act of separating one or more distinct phases from another in a process which uses physical differences in the phases (such as particle size or density or electric charge). The whole of the phase separation spectrum is illustrated in Table 1.1, which covers the separation of distinct phases as well as completely mixed ones. In principle, this book is only concerned with the second half of Table 1.1 – the separation of distinct phases. However, as with any attempt to classify things in the real world, there is some overlap with the first half of the table: some membrane processes normally classified with filtration actually operate by molecular diffusion, while one major filtration mechanism involves adsorption (and many adsorbers act as filters as well).

Table 1.1 The separation spectrum

Completely mixed phases	
Vaporization	Distillation
	Evaporation and drying
	Sublimation
Condensation	
Sorption	Absorption
	Adsorption
Phase transfer	Diffusion
	Leaching and Extraction
Distinct phases	
Solid from solid	Screening and Elutriation
	Classification
Solid from fluid	Filtration
	Sedimentation
	Flotation
	Scrubbing (wet or dry)
	Electrostatic precipitation
Liquid from liquid	Sedimentation
	Coalescing
Liquid from gas	Demisting
	Sedimentation
Gas from liquid	Defoaming
	Sedimentation

That said, it is in the lower part of Table 1.1 that the main concern of this book lies, primarily in the separation of solid contaminants from liquid or gas flows, by filtration or sedimentation processes. To a lesser extent, liquid/liquid and liquid/gas systems are considered (for which true filtration is not used), although sedimentation systems are employed, together with filtration-like processes, such as demisting.

A filter is basically a device for separating one substance from another, and to do that it requires the placing of a filter medium in the way of the fluid flow, so as to trap the solids in some way. The filter then becomes any contrivance that is able to hold the filter medium in the best way to achieve the purpose of the filter process.

The most common of the distinct phase separation processes given in Table 1.1 are the solid/fluid ones: solid/gas separations being exemplified by the treatment of process and boiler exhausts in baghouses, and by the panels used in building air conditioning; solid/liquid separations cover the enormous range of filter types from the simple cartridge filter to the complex machines such as the rotary pressure drum filter. Most of the inertial separations (cyclone and centrifuge) and sedimentation systems are also found in this category.

This book aims to cover, in a descriptive fashion, the whole spectrum of filtration and its closely related separation processes. It continues in this section with some general material on filters, their characteristics, specification and testing. The importance of the filter medium to filtration performance is acknowledged in Section 2, devoted to descriptions of filter media. This is followed by a series of descriptions in Section 3 of all of the relevant filtration equipment.

The equipment descriptions are followed by three sections on filtration applications: Sections 4 and 5 deal with liquid filtration, and Section 6 with gas filtration. The penultimate section looks at types of equipment other than filters that are used for clarification, and the book finishes with some guidance on equipment selection.

Filtration technology

The two major branches of physical separations technology, filtration and sedimentation, work by quite different mechanisms. Filtration operates entirely on particle or droplet size (and, to some extent, shape), such that particles below a certain size will pass through the barrier, while larger particles are retained on or in the barrier for later removal. The separating size is a characteristic of the barrier, the filter medium. The wide range of filter designs is very largely a consequence of the need to handle the accumulated solids that collect in the filter, although the need to pack as much filter medium area into a given equipment floor space (or volume) can be another design decider. The operation of a filter usually needs a pressure differential across the filter medium, and this can be effected by means of fluid pressure upstream of the medium (pressure filters) or suction downstream (vacuum filters).

Sedimentation, on the other hand, operates on the density of the particle or droplet, or, more correctly, on the density difference between the suspended particle and the suspending fluid. It is the force of gravity working on this density difference (or the much higher centrifugal force operating in a centrifuge) that causes separation by sedimentation – either of a solid from its suspension, or of a lighter solid from a heavier one. Particle size also has a part to play in sedimentation – a larger particle will settle faster than a smaller one, of the same density. Settlement area is the prime consideration in sedimentation, with throughput being directly proportional to available area, which is why the extra cost of a sedimenting centrifuge will often pay for itself because of the much smaller space that it occupies.

Solid separating technologies have two prime purposes: the removal of unwanted solids from suspension in a fluid (which may itself be a wanted product or a waste that needs cleaning prior to discharge), and the recovery of a wanted solid product from its suspension (often following a prior crystallization or precipitation step). Either kind of equipment, filter or sedimenter, may be used for either of these purposes, although it is true that most solid recovery is achieved in filters or sedimenting centrifuges.

The particle sizes covered by filtration range from the large pebbles of the mineral sector's screens to the ultrafine particles and large molecules of the membrane ultrafiltration systems. Most systems involving contaminant removal are concerned with fine particles – fine enough, for example, to have stayed suspended in atmospheric air for long periods of time.

The mean particle size, and the particle size distribution, will both have a major influence on the type of filter chosen to treat a suspension, a choice that would be made in order to produce the most filtration-efficient, energy-efficient and cost-effective solution. The apparent filtering range of a particular type of filter can be misleading in terms of both efficiency and cost-effectiveness. The finer the filter, the more readily it will become clogged by coarser particles, so that, where very fine filtration is required, it becomes both more efficient and more cost-effective to filter in stages, using two or more filters in series with progressively decreasing cut-points. Thus, a full system might include an initial strainer, followed by a thick medium filter, and then an ultrafilter for the final stage (or even this whole prefiltration system ahead of desalination by reverse osmosis).

The types of contaminant present, and their concentrations, will obviously depend on the environment in the case of atmospheric contamination (or on the prior history of the liquid for a suspension). Air pollution can be treated by means of a large baghouse filter, capable, with appropriate bags fitted, of filtering down to below 0.1 μm, which means just about all likely contaminants, but its use would only be justified in special circumstances (such as an industrial air flow), and simple panel filters would probably be suitable for most other applications.

The size of the separated particle is used to delineate the terms used for the various filtration processes. Thus 'filtration' (or more specifically, nowadays) 'macrofiltration' is used for separating particles in the approximate range of 1 mm down to 5 μm (with 'screening' used for particles above 1 mm, without an upper limit). From 5 μm down to about 0.1 μm the process is termed *microfiltration*, while below that the term *ultrafiltration* applies. Ultrafiltration covers the finest distinct particles (such as colloids), but its lower limit is usually set in molecular weight terms, measured in Daltons.

Below ultrafiltration in size terms come nanofiltration and reverse osmosis, which look just like filtration processes and are often counted in with them – they have a liquid flow, and a semi-permeable membrane is placed as a barrier across this flow. However, NF and RO differ from UF in operating principle: the liquid treated is now a solution with no (or extremely little, if properly prefiltered) suspended matter. The membranes have no physical holes through them, but are capable of dissolving one or more small molecular species (such as water in the case of RO desalination) into the membrane material itself. These species diffuse through the membrane, under the high trans-membrane pressure, and emerge in their pure state on the other side.

Whilst many filters or sedimenters have a range of applications for which they are well suited, the application ranges are by no means unique, and the engineer seeking a 'correct' separation solution may still be faced with a choice among several types from which to make the best (the most efficient, the most cost-effective) selection. The dewatering of sludges, from production processes or from waste treatment, for example, was, for many years, the province of the filter press. The belt press was developed very much to capture some of this market. Then good and reasonably economic coagulants were developed, which made the solid/liquid task easier, and vacuum belt filters and decanter centrifuges became effective tools for this task.

A final point on technology, although by no means an unimportant one, is the need for the filter, and especially the filter medium, to be materially compatible with the suspension and its components. This requires little attention in, for example, the filtration of ambient air, but is of vital concern where the gas is hot (as from a furnace), or the liquid is corrosive (as in mineral acid filtration), or the solids are abrasive. Filtration in the nuclear industry especially imposes problems not only of resistance to radiation, but of difficult or impossible access once the filter has been used.

The filtration business

There is hardly a human activity, industrial, commercial or domestic, that is not affected by filtration. It is a very widely used process, from the kitchen counter top water filter to the enormous wastewater treatment plants, or from the delicate membrane ultrafilter to the rugged tipping pan filter of a mineral processing works. It has a major processing role in many industries, and all service applications, such as hydraulic control systems, would literally come to a halt without it.

It is estimated that the total world market for filtration and sedimentation equipment in 2007 will be in the region of US$38 billions, expanding at a rate comfortably in excess of that of the global economy. The business is dominated by liquid processing, which makes up about 84% of the world market, and similarly by clarification duties, which are close to 70% of the market – so that the contamination removal process, the prime topic of this book, represents more than two-thirds of the business of filtration and sedimentation.

The usage of filtration and similar separation equipment is quite evenly spread throughout the economy, with the two largest end-use sectors being those in which the largest number of individual filters are found. The domestic and commercial sector with its many water filters (and coffee filters, and suction cleaner filters) is one; and the transport system sector with its huge number of engine filters for intake air, fuels and coolants, is the other. The sector shares of the 10 largest end-user sectors are given in Table 1.2, from which it can be seen that the total of the bulk chemicals and fine chemicals sectors (16.4%) would make a total chemicals sector into the second largest of the identified end-user groups.

The fastest growing of these sectors is expected to be that for fresh and wastewater treatment (the third largest sector), followed quite closely by the fine chemicals and pharmaceuticals groups.

The separations business is becoming increasingly more technical, with more stringent demands being continuously placed upon its products; in parallel with

Table 1.2 Sectoral market shares, 2007

End-use sector	Market share (%)
Domestic, commercial and institutional	17.9
Transport equipment and systems	15.9
Fresh and wastewater treatment	10.3
Bulk chemicals	9.9
Food and beverage production	7.5
Fine chemical, pharmaceuticals and biochemicals	6.5
Power generation	6.3
Pulp and paper	5.1
Medical and health	4.8
Electrical and electronic materials and equipment	3.5

this, there is the obvious need for equipment suppliers to ensure that they have on hand the highly knowledgeable engineers able to analyse and solve the consequent problems.

The environment

At the time of writing, there is much concern being expressed about the global environment and human influences upon it. Whether it is to do with climate change and its probable human cause; continued starvation in large regions of an otherwise rich world; or the conversion of a runaway consumption to a sustainable expansion, large areas of the world are beginning to take note of changes in their environment, and of the need to make parallel changes to the way in which life is conducted; in particular, in energy consumption and fresh water provision.

The general importance of environmental protection justifies mention of the topic here – because filtration has a major role to play in many of the schemes trying to achieve this protection. Environmental protection legislation has been in place in the US and Europe for several decades now, but the beneficial effects are only just beginning to appear. Similar processes exist in other developed regions, but the developing countries have hard decisions to take over whether to let expansion run loose, to satisfy their people's natural wish for higher standards of living, or to rein it in, to give sustainability a chance.

The market forces exerted by the imposition of environmental legislation are an important driver for the filtration market. The legislation calls for waste minimization and for the treatment of unavoidable waste streams to continually higher standards, both of which are well met by available and developing types of filtration equipment.

The separations industry itself can make a useful contribution to energy conservation: all filters need some kind of driving force, especially in the higher pressure membrane systems, and the design of filter systems to minimize their energy demands is an important feature of the development of such systems.

1B. CONTAMINANTS

Contaminants, i.e. minor impurities, are normally present in all fluids, natural or processed. Where the level of contamination in the fluid is significant, i.e. too great for that fluid to be consumed, or used for its proper purpose, or to be subsequently processed, then it becomes necessary (or in some cases legally obligatory) to remove these impurities from the carrying fluid, so as to reduce contamination to or below acceptable levels.

These contaminants may be rigid or deformable solids, when they can be separated by a filter, or perhaps by a sedimentation process. Distinct liquid droplet contaminants can also be removed in this way, using filter-like separators or sedimentation. As indicated in Section 1A, where these contaminants are completely mixed in the carrying fluid (gas dispersed in a gas, liquid dissolved in another liquid), then filtration or sedimentation are not suitable for their separation, and phase change processes such as adsorption (e.g. with activated carbon, or perhaps molecular sieves) must be used. The middle ground is occupied by some solid/liquid or liquid/liquid solutions whose value is such as to justify purifying by means of a membrane separation process.

The kind of situation being discussed here involves the presence in a fluid of some material, solid or liquid, that would be harmful to the consumer or other user of that fluid if it remains in that contaminated state. Thus a homogeneous suspension may carry rogue particles of a size much larger than that in the emulsion – these can usually be removed quite easily by a scalping strainer. The coolant used to lubricate and cool the cutting zone of a machine tool is a quite complex mix of liquids, which is too expensive to throw away. After use it will normally be contaminated with the metal particles (swarf) removed from the item being machined, so that before being recycled it must be freed of such contamination, in a filter, or settling tank or centrifuge. The air in the modern city street is quite highly polluted with diesel fumes among other things, and many people are now wearing personal respirator masks to protect themselves against these impurities in the air that they breathe. Surface water abstracted for drinking water production is frequently coloured to an unacceptable level by small quantities of colloidal solids, which may require ultrafiltration for their removal.

As can be seen from Figure 1.1, the kinds of impurity carried in the atmospheric air vary widely in size, with the greater proportion being invisible to the naked eye (the limit of human vision being about 20 μm). Such small particles, either in the air or settled out into a liquid stream, are perfectly capable of sticking between adjacent machinery surfaces and causing wear, or of collecting together to block a liquid passage and so interfere with flow.

The separation of such contaminants from working or process fluids is very largely a task for filtration, in ways to be described later in this book. The only significant decontamination process not using filters is the large volume process of settlement of fresh or wastewater. Purifying processes on gas or liquid streams are often required to treat such large volumes of fluid. It obviously pays, therefore, to treat no more than is absolutely necessary – the personal gas mask, for example, rather than

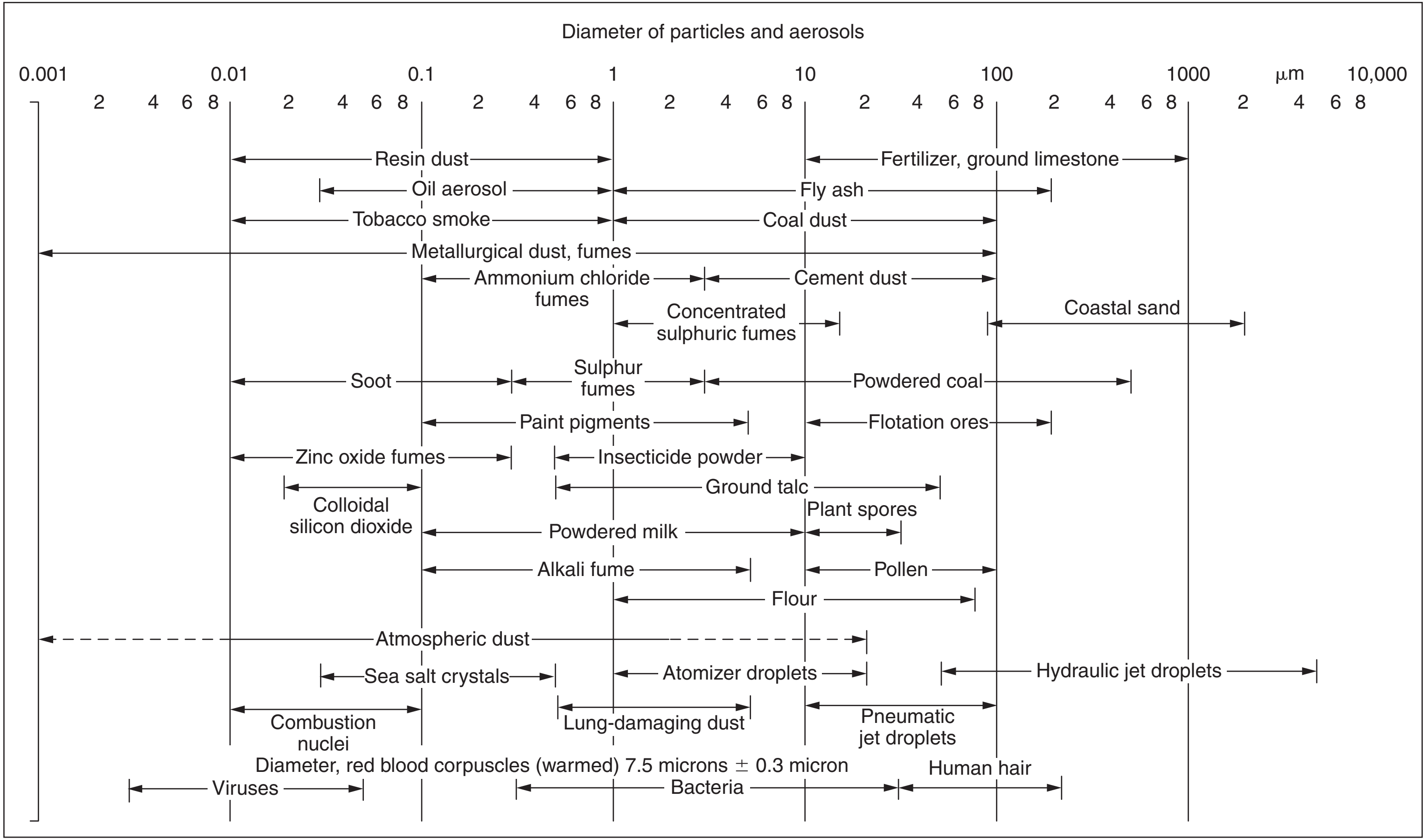


Figure 1.1 Impurities in air

all of the ambient air. Another approach to the treatment of large flows for contaminant removal is by taking off a sidestream and cleaning this completely, before mixing it back into the main flow. With the correct ratio of sidestream to main flow, the final composition can be made acceptable.

It must be remembered that protection against contamination can often be a two-way process. Thus, a working space may need protection from the contaminants in ambient air by means of the provision of a controlled atmosphere. However, its working materials may be sufficiently toxic that the external environment may need protection against unintentional emissions from inside the space, which means that all vents from the working space, of whatever size, will need to be provided with adequate filters or adsorbers.

Particle settlement

The critical factor in the creation and maintenance of dust-laden air or particle contaminated water is the nature of the particle, in terms of its size and its relative density. This is because of the development of a constant, terminal velocity by a particle falling freely through a fluid, whose value, as demonstrated by Stokes' law, is:

- directly proportional to the square of the particle diameter
- directly proportional to the difference between particle and fluid densities
- indirectly proportional to fluid viscosity.

This relationship is strictly true only for spherical particles falling while isolated from one another by some distance. Non-spherical particles are accounted for by the use of an effective diameter (often determined by the reverse process of measuring a terminal velocity and calculating back to the diameter). Stokes' law holds well enough in the case of fluids with a low solids concentration such as concerns a study of contaminant removal.

If the particle size is small enough so that the terminal velocity is very low, or if there are random movements in the fluid at velocities in excess of this terminal figure, then the particle effectively does not settle out, and a stable suspension results – which may then need decontaminating. The settling velocity in air of a spherical particle, whose specific gravity is 1, is given by:

$$1.8 \times 10^{-5} \times d^2 \text{ metres per minute}$$

where d is the particle diameter, expressed in μm. An array of values for terminal settling velocities in air for a spherical particle with sg = 1 is given in Table 1.3.

Airborne contaminants

As shown in Figure 1.1, airborne particles may range in size from 1 nm (0.001 μm) up to 1 mm or more. The larger particles, such as might come from heavy foundry

Table 1.3 Approximate settling velocities in still air (normally spherical particles of sg = 1)

Particle size µm	Settling velocity	
	m/min	ft/min
1000	245	800
600	183	600
500	150	500
400	137	450
300	122	400
200	75	250
100	18	60
90	14.5	48
80	11.5	38
70	9.0	29
60	6.5	21
50	4.5	15
40	3.0	9.5
30	1.6	5.35
20	0.7	2.33
10	0.2	0.60
5	0.045	0.15
1	0.0018	0.006
0.1	0.000018	0.00006

dust or ground limestone, would need updrafts of the order of 4 or 5 m/s to maintain them in suspension. For the very smallest, however, the settling velocities are so low as for them to remain in suspension all the time – with the Brownian motion of the molecules of the fluid ensuring that they do so remain.

Particles in air suspension will range downwards from 100 µm. Down to 20 µm they will be visible to the naked eye, while on down to 0.1–0.2 µm they can be observed with a conventional microscope. The major problem particles that are viruses are smaller than this, and so that much more difficult to remove.

Typically, some 90% by weight of all airborne particulate impurities range from 0.1 to 10 µm in size, although this range and the actual concentration of solids will vary markedly, dependent upon the immediately local environment and wind activity – a desert sandstorm is far worse than any industrial activity.

If the air is, indeed, in motion, then quite large particles will be held in suspension, particularly if the flow is turbulent. Thus 10 µm particles will be held up by quite gentle air movements, while velocities of 0.3 m/s in a vertical direction, a quite common flue gas regime, will keep 100 µm particles suspended.

A somewhat different picture of contaminant size ranges is given in Figure 1.2 which also shows the capture ranges for several different types of separation equipment.

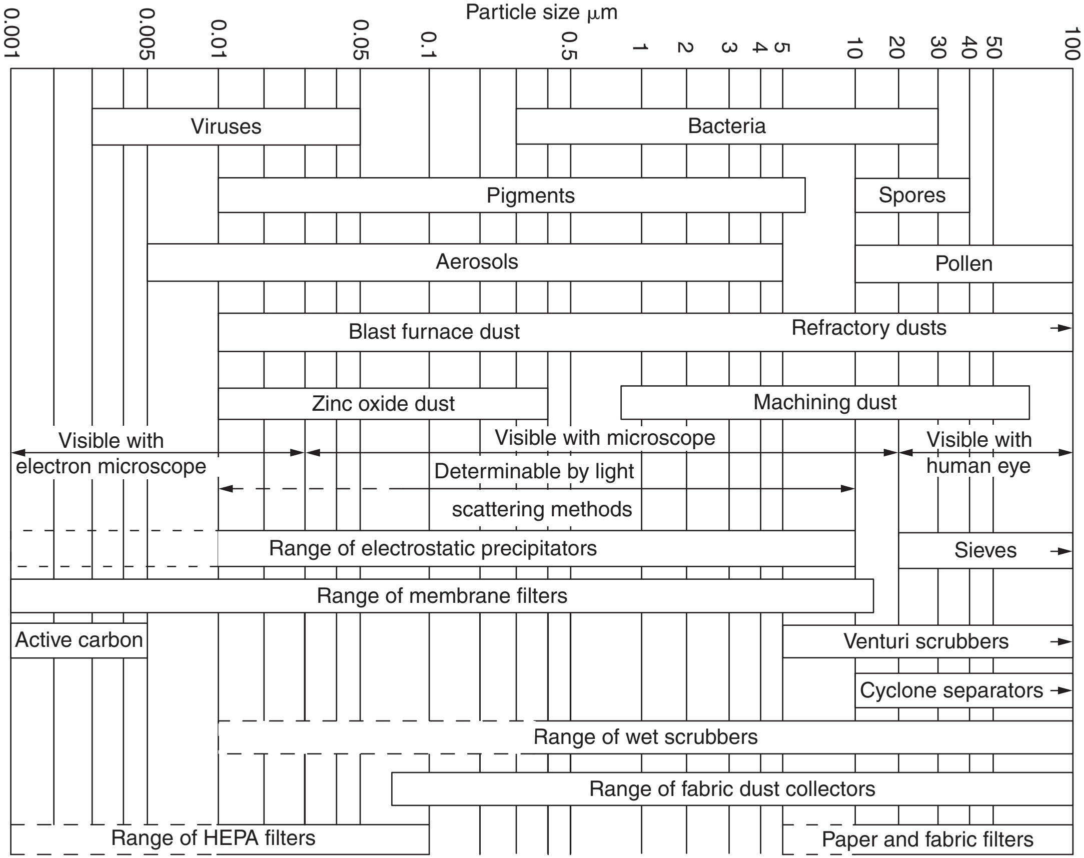


Figure 1.2 Contaminant sizes and separators

Effect on humans

The average person breathes in about 12.5 m^3 or 16 kg of air each day. This is normal atmospheric air, which is far from clean. The breathing of contaminated air, which may well contain particularly aggressive substances, is a frequent cause of ill health, contributing to the common cold and influenza, emphysema, headaches, eye irritation, coughing, dizziness, and the build-up of toxins in the bloodstream.

Impurities enter the body through the mouth and nose, and gradually becoming deposited on the bronchial mucous membrane. At the initial stage of deposition, the bronchial membrane itself is able to provide protective counteractions in the form of sputum and coughing. This physical adjustment becomes impossible as a result of repeated inhalation of contaminants and their inevitable deposits over an extended period. As a consequence, the functions of the bronchi become abnormal. In the lungs, congestion of the alveoli and irreversible fibrinous changes occur, leading perhaps to pulmonary emphysema. Functional deterioration of the lungs will affect the heart adversely, leading to heart disease.

This somewhat over-dramatic picture nevertheless highlights the need for clean air for all human activity. Legislation such as the Health and Safety at Work Act is taking care of the industrial environment, but only slow progress is being made to protect the general ambient air. Steps towards alleviation of diesel engine pollution are certainly in the right direction.

Effect on machines

Most engines take in air at a considerable rate: the factor of interest here is the weight of solids that could be taken to the engine. The average automobile engine inducts something like 9 or 10 m^3 of air for each litre of petrol burnt in its cylinders, which corresponds to an annual intake of between 30,000 and 60,000 m^3 of air per year. The solid particle content of this air is likely to be 0.3 to 0.6 kg, which, in the absence of good filtration, would all deposit in the engine where its abrasive nature would soon do serious damage. These figures correspond to a dust concentration in the air of 10 mg/m^3, and much worse conditions are readily identified: a mineral processor's rock crusher could be working in a dust concentration up to 20 times that figure. From another perspective, a land-based gas turbine could easily be taking in tens of thousands times the air volumes of an automobile.

Inducted solids will tend to accumulate as deposits on pistons, cylinder heads, valves and other internal components, with the strong possibility of their being bonded in place by the oil film normally on these surfaces. The oil film will thus accumulate an abrasive content. Meanwhile, the dust still in the air will be washed out by the oil mist, to collect in the lubricant and then be circulated through the machine with dire consequences. In the drier interior of a gas turbine, the suspended solids will quickly wear away the turbine blades.

Clearly such dust intake levels cannot be tolerated, and filtration systems must be installed to remove the dust. Fitting a filter involves a compromise; firstly as to its cut point, and secondly as to its energy needs. The finer the filter, the more dust will be removed but the more energy will be expended in achieving that removal. It will clog faster and so need cleaning or changing more quickly. So only the finest necessary filter should be fitted, but it must remove particles that are likely to jam in the narrow spaces of the engine. Particles of sizes down to about 10 µm can do damage, and this is probably the level of particle cut-point that should be sought.

Obviously, the filtration requirements for an engine will depend markedly upon the environment in which it is to be used. A stationary location in country air will be less demanding than the use in an urban area, less again than in a heavy industrial use.

It must not be forgotten that all machinery is capable of producing contaminants by internal wear or from degradation of the materials being handled. Wear products will be at their peak when the machine is new and is being bedded down, and at the same time residues from its manufacture (such as grains of foundry sand) could also be present. Filtration must also be provided to protect the machinery from such materials, and the type will depend very much on the nature of the machine being protected.

Liquid contaminants

Whilst the presence of liquid water droplets from rain or marine spray cannot be avoided, the more serious situation with water drops comes in the provision and use of compressed air systems. If the intake air is close to saturation before compression it takes but a small increase in pressure for the water vapour to condense into drops. These drops can be a problem in the subsequent usage of the compressed air, and quite complex chains of filters and filter/dryers, together with intercoolers, are used to reduce the water content to an acceptable level.

The compressor may also be a source of oil spray such that oil droplets are formed in the product air stream. A major problem here is that oil droplets are a health hazard, as well as becoming taken up as an oil/water emulsion. Here again filtration is necessary to deal with the problem, and separation of droplets at least in the 0.4 to 4 µm size range may be required from the health point of view alone.

Applications

It will have become apparent that the decontamination applications for gaseous systems are very important, and can involve very large flow volumes. The applications include:

- cleaning of inlet air entering living spaces
- cleaning of air entering work spaces, and protection from work space exhausts
- machinery and engine air intakes
- respirators and breathing apparatus
- compressed air treatment and pneumatic systems
- engine exhausts
- process and boiler furnace exhausts.

Liquid flow contaminants

Contaminants will enter liquid flows from their environment and from any prior treatment or contamination that they have undergone. The prime concern over liquid contamination now and into the foreseeable future is the provision of drinking water free of harmful bacteria and viruses, a provision that is still unavailable to vast areas of the world.

Because of the much wider range of processes involving liquids, there is a correspondingly wide range of contaminants in liquid systems, at least if defined by chemical nature. Table 1.4 shows a reasonably complete list of the techniques used for detecting and determining the properties of solids suspended in liquids.

Applications

As has just been implied, there is a large number of contaminated liquid systems throughout industry, commerce and domestic life. Some of the more important of the working fluid decontamination processes are the:

- production of potable water from ground and surface sources
- production of ultra-pure process water
- treatment of wastewaters to prepare them for discharge
- preparation of boiler feed water and the recycling of condensate
- treatment of process wastes prior to recycle
- treatment of wash water of all kinds for re-use
- processing of transformer oils
- cleaning of machine tool coolants and cutting fluids
- cleaning of hydraulic system fluids
- treatment of all engine liquids: fuels, lubricants and coolants
- cleaning of machine lubricants.

In addition, there is a wide range of product streams that need polishing or freeing from the final bits of visual impurity – from beer to shampoo to engine oil – while most process filtration steps, in which a solid product is recovered, perhaps by a filtration step, produce a filtrate that may need clarifying before it can be recycled or used in some other way.

The treatment of waste or surplus waters for recycling is becoming a major application as so many industrialists now try fully to ‘close their water cycle’. This can be seen in the paper mill, and should soon be seen on the domestic scale with the recycle of ‘grey water’.

1C. SURFACE AND DEPTH FILTRATION

The basis of the particular mechanical separator that is called the filter is the placing across the fluid flow of a barrier, the filter medium. This acts like a porous screen, allowing those arriving particles – which are below a certain size – to pass through the openings that give the medium its porosity, together with the carrier fluid. Those

Table 1.4 Techniques for particle detection in liquids

Technique	Size Range	Monitor			Comments
	µm	IN	ON	OFF	
	.01 .1 1 10 100 1k	line	line	line	
Capillary Hydrodynamic Fract.	■■■■■			X	
Dielectric Constant	■■■■■■■			X	General level
Electrical Conductivity	■■■■■■■■	X	X		Chip plug
Electrical Sensing Zone (ESZ)	■■■■■■■■■			X	
Electroacoustic	■■■■			X	
Electro Rotation Assay (ERA)	■■	?	?	X	Water mainly
Filter Blockage	■■■■■		X	X	
Gravimetric	■■■■■■■■■			X	Filtered
Image Analysis	■■■■■■■■■■		X	X	After filtering
Inductance	■■■■	?	X	X	
Magnetic Attraction	■■■■■■■■	?	X	X	
Optical					
Foreward Reflection	■■■■■■■■■		X	X	Low levels
Fraunhofer	■■■■■■■■■■■		?	X	
Light Obscuration	■■■■■■■■■■		X	X	
Light Scatter	■■■■■■■■■■		X	X	Clear liquids
Turbidity	■■■■■■■■■■■■■	X	X	X	Overall view
Phase/Doppler Scatter	■■■■■■■■■■■			X	Mainly sprays
Photometric Dispersion	■■■■■■		X	X	General level
Photon Correlation Spec.	■■■■■■			X	Clear liquids
Time of Transition	■■■■■■■■■	X	X	X	
Radioactivity	■■■■■■■■■■■■■	X	X		Pretreated
Sedimentation (gravity)	■■■■■■■■■■■■			X	Sphere based
Sedimentation (centrifugation)	■■■■■■■■■■			X	Sphere based
Sieving	■■■■■■■			X	Shaker need
Silting	■■■■■■■■		X	X	Under R&D
Sound Absorption	■■■■			X	General level
Ultrasound	■■■■■■■■■■	X	X	X	Water mainly
Visual Appearance	■■■■■■■■			X	Microscope
Wear of Thin Film (Fulmer)	■■■■■■		X	X	

particles that are too large to pass are retained on (or in) the medium, for subsequent removal in some other way. [It should be noted here that in some filters the collected solids are continuously or intermittently brushed or scraped from the surface of the medium, into a collection hopper below the filter. While in others the filter medium is withdrawn continuously or intermittently from the filtration zone so that the collected solids may be removed from the medium in another part of the filter.]

The nature of the filter medium is critical to the filtration process, and the various types of media will be described in Section 2. Suffice it to say here that there are ten broad types of media material to be considered. Of these ten types only one does not have a version that is fibrous in structure. All the rest are entirely fibrous, or have a significant component in fibrous format. It follows that, to find how filtration works, it is necessary to examine the way in which a bed of fibres can stop a particle moving towards and through it. The process is illustrated in Figure 1.3, which shows the cross-section of a single fibre in a fluid flow from left to right, carrying some particles in suspension.

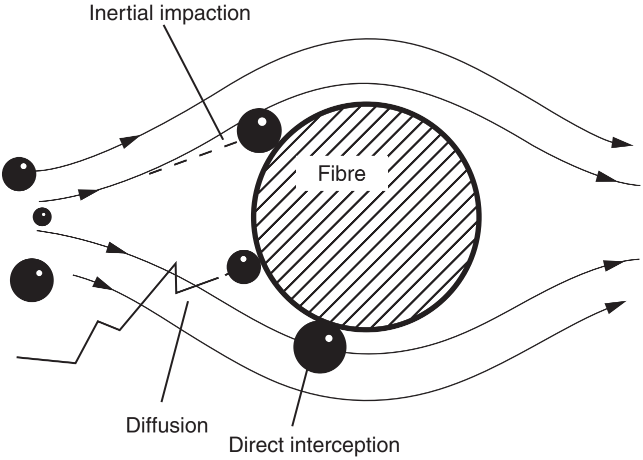


Figure 1.3 Particle collection mechanisms

The first major point to note is that any particle, in the absence of electrical charges on fibre or particle, once brought close enough to the fibre, will be attracted to the fibre, until contact is made, and then the particle will stay put. The attractive forces are quite weak (known as van der Waal's forces), but are sufficiently strong to hold the particle on the fibre surface once it is there, independent of the way in which the particle arrived. The particle should be very close to the fibre for this process to occur, but once it has been trapped, then the trapped particle acts like an extension of the fibre, and can then, in its turn, trap other particles.

It follows that, if the fluid flow is such that the particle is brought into contact with the fibre, it will be caught and held by the fibre – it has been filtered. Another point to remember is that the flow inside the medium is close to, if not actually, laminar, so that the fluid flows in smooth streamlines around obstacles in its path, as shown in Figure 1.3. Unless otherwise disturbed, the particles follow these streamlines through the bed of fibres. If the particle is small, it will be contained within a packet of streamlines, and will be swept past the fibre and onwards without being caught.

As the streamlines bend round the obstacle, they carry particles with them, and if a particle in so doing is taken to a distance of less than half of its diameter from the fibre surface, as has happened to the lowermost particle in Figure 1.3, then it will come into contact with the fibre and so get trapped. This mechanism is known as *direct interception*, and, by definition, it must happen on the flanks of the fibre, not directly in front of it.

In turning their path to pass by the fibre the streamlines take the suspended particles with them. However, a larger particle (or a particle moving fast) will carry too much inertia to make the turn. It will then cross the streamlines and collide with the fibre, and be trapped. This mechanism is termed *inertial impaction*, which has happened to the topmost trapped particle in Figure 1.3.

Another group of particles do not stick to the streamlines but meander about, in and across them. This is *diffusion* behaviour, affects mainly small particles, and is largely caused by the Brownian motion of the carrier fluid. The particle thus pops out of the streamline pattern near to the fibre surface, and once again is trapped, as is the case for the smallest of the trapped particles shown in Figure 1.3.

These are the three main mechanisms for particle entrapment in a bed of fibres, but there are others. For example, the small particle on the left of Figure 1.3 is going to find it difficult knowing which way to go around the fibre. It will probably be carried straight towards the front face, but before it reaches it, will become involved in the fluid eddy pattern that must exist just in front of the fibre. It is then likely to exit from this pattern either into the by-passing streamlines, or by getting trapped on the front surface of the fibre.

The above paragraphs describe the mechanisms whereby particles or droplets can be attracted to and deposited on the fibres of a filter. It will be apparent that uniformly sized particles will be removed in the manner shown in Figure 1.4, with each particle passing through the mass of fibres until it is trapped.

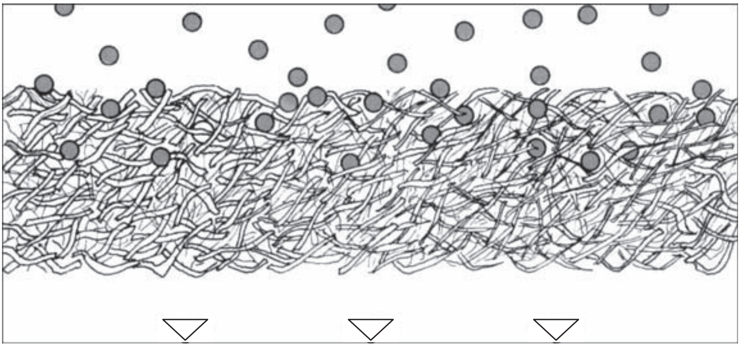


Figure 1.4 Filtration of uniform particles

It will also be apparent that, although very fine particles can pass right through the medium, the mass of fibres can trap particles significantly smaller than the flow channels (pores) in between the fibres, by any of the above mechanisms. This can be seen in Figure 1.5, which shows a highly magnified view of a fibre mass holding two quite small particles (around 1 μm in size, at a magnification of 9500×).

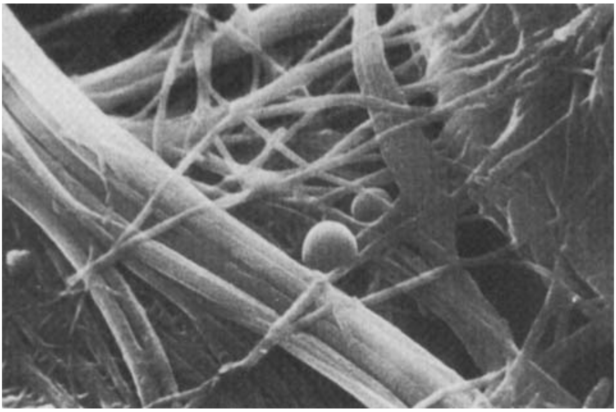


Figure 1.5 Fine particles trapped in a fibrous mass

This ability to trap particles smaller than the apparent aperture size is a very important characteristic of filter media, and shows that media need to be tested.

Surface *vs* depth filtration

It has been stated that a filter medium is a porous (or at the very least semi-permeable) barrier placed across the flow of a suspension to hold back some or all of the suspended material. If this barrier were to be very thin compared with the diameter of the smallest particle to be filtered (and perforated with even sized holes), then all the filtration would take place on the upstream surface of the medium. Any particle smaller than the pore diameter would be swept through the pores, and any particle larger than that (assuming the particles to be rigid) would remain on the upstream surface. Some of the larger particles, however, would be of a size to settle into the individual pores and block them. The medium surface would gradually fill with pores blocked in this way, until the fluid flow reduced to below an acceptable level. At this point filtration would be stopped and the medium surface would be brushed or scraped clean (although many automatic filters have their surface continuously brushed or scraped).

This filtration mechanism is termed *surface straining*, because it works entirely on the relation between the particle size and the pore size in the screen. Unless the particles are easily deformable, then surface straining will separate solids in the feed suspension absolutely on the size of the pores in the filter medium. This mechanism is that working in screening through a perforated plate or single layer of woven wire or plastic mesh of precise weave. It also applies in the range of metal edge and similar cartridges where the ‘pores’ are actually precisely formed slots between adjacent discs or turns of a helical ribbon (media formats are described in more detail in Section 2).

Most real media are, of course, not infinitely thin, but have a finite thickness in the direction of fluid flow, while most pores through such material vary in diameter along the fluid path. A second mechanism, termed *depth straining*, then applies when a particle moves through a pore until it meets a point where the pore is too small, and the particle is held entirely because of its size. The pore then is blocked, and remains so until the filter medium becomes too clogged in this way for it to have any further use. At this point it must be discarded, or, preferably, blown free of the trapped solids, by a reverse flow of fluid.

In the same way that particles can be trapped in a bed of fibres by the adsorption processes described earlier, so can fine particles moving through a tortuous path imposed by an irregular pore be trapped on the pore surface by the mechanisms of direct or inertial interception or diffusion. This process is known as *depth filtration*, and is shown in Figure 1.6. Pore blockage also occurs with this mechanism, as particles become trapped to one another, although no pores become absolutely blocked, because the fluid can still flow through the spaces between the particles. As before, a completely clogged medium would need to be discarded or cleaned by reverse flow (or perhaps chemically).

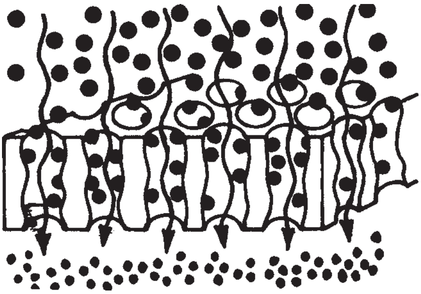


Figure 1.6 Depth filtration

In practice, the effects of depth straining and depth filtration are effectively the same – the medium clogs because of particles trapped in the pores – and difficult to tell apart, so both mechanisms are usually grouped together under the title of depth filtration.

These mechanisms – surface straining and depth filtration – are the clarification processes that are the prime topic of this book. This is because most clarification applications involve low solids concentration.

Where solid concentrations are higher, as is the case with a large number of process separations, a different mechanism is called into play, which is the development of surface straining. Now, because of the high concentration of solids in the suspension, the particles jostle with one another at the entrance to each pore and, after a very short period when some small particles escape through the pore, the particles bridge together across the opening to the pore. These particle bridges then act as the filter medium to allow layers of particles to form upstream of them and the fluid to flow through these layers to be filtered. The build-up of particles on the filter medium produces a cake of separated solids, and the mechanism is termed *cake filtration*, with actual separation by depth filtration within the thickness of the cake, and surface straining on its upstream face. This mechanism is illustrated in Figure 1.7.

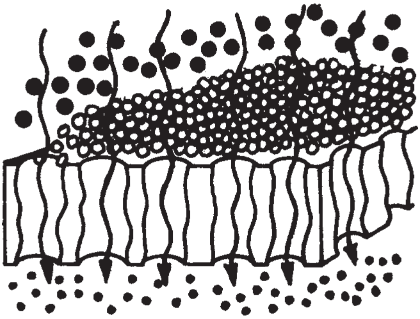


Figure 1.7 Cake filtration

Cake filtration presents complicated problems because the cake can be more or less compressible under the force of the pressure differential across the cake. Some clarification processes do employ cake filtration – such as exhaust gas cleaning in baghouses or the treatment of some dilute liquid slurries in bag filters – where the accumulated cake is usually blown free from the surface of the bag by means of a reverse flow of fluid.

1D. FILTER RATINGS

Filters are rated according to their ability to remove particles of a specific size from a fluid suspension. There are many different methods in which performance may be specified in this way, and quantitative information as to filter performance must always be associated with the corresponding test methods used.

The object of a filter is to remove solid particles from a fluid stream either completely, or at least down to a specific size. Apart from specially prepared test suspensions, most real suspensions contain a wide range of particle sizes and the actual efficiency of removal is then a compromise between the amount of solid allowed through the filter and the energy required to capture the rest (i.e. the fineness of the medium, which dictates the energy consumption by the filter, and hence a large part of the operating cost).

Absolute ratings

Given that a filter may not be able to remove all of a suspended solid, there will, nevertheless, be a particle size cut-off point above which no particle should be able to pass through the filter. The cut-off point thus refers to the diameter, usually expressed in micrometres (μm), of the largest particle that will pass through the filter, although this is not the smallest particle retained by the filter, because smaller particles are quite likely to be retained, by the adsorptive mechanisms described in the previous chapter.

If the filter medium has an exact and consistent pore size or opening, then this cut-off point can be termed an *absolute rating*. Most real media, of course, do not have exactly consistent pore sizes, while tests to assess filter ratings are normally undertaken with spherical particles (because these are easiest to size accurately), whereas very few real suspensions contain spherical particles.

The actual shape of the particle may, in fact, have a marked effect on the effectiveness of the filter. An acicular (needle-like) or plate-like particle can pass through a pore of size considerably less than the particle's nominal diameter, as shown in Figure 1.8. The figure shows an acicular particle, but the illustration could as easily represent a plate-like particle passing through a slot in a metal-edge filter. This example shows the care that must be exercised in selecting a protection filter to ensure that adequate protection is, in fact, given.

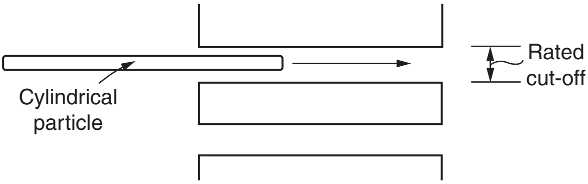


Figure 1.8 Abnormal particle passage

The chance of such a lining up of particle and pore as illustrated in Figure 1.8 may be rare, but if the potential damage that could be done by such a particle having got through the filter is serious, then steps must be taken to ensure that it can never happen. With depth filtration the chances of passage of this kind of rogue particle is minimized. Another insurance against this risk is achieved by using two separate layers of filter medium in series, so minimizing the existence of a continuous pore through both layers.

The occurrence of large continuous pores is also reduced because most real filtration systems do create a layer of filter cake, even if quite thin. These solids decrease the permeability of the medium and increase the filtration efficiency. This explains why the performance of a filter can often exceed its given rating, based on the performance of a clean element, and also why test figures for identical elements can differ widely with different test conditions.

Some types of filter media, such as paper, felt and woven cloth, have a variable pore size, and so do not have an absolute rating. The effective cut-off is largely determined by the random arrangement of pores and the thickness of the medium. The performance may then be described in terms of a nominal cut-off or nominal rating.

It may be argued that the term ‘absolute rating’ is not, in most cases, a realistic description. Strictly speaking, an absolute rating is, as its name infers, absolute, and no particle larger than that rating can pass through the filter. This limits the type of medium that can have an absolute rating to those of consistent pore size, capable of retaining 100% of particles. It is also likely that the absolute rating would, from the point of view of being sure, need to be higher than a practically observed mean or nominal rating. Even with consistent pore sizes or openings, an absolute rating is not realistic if based on the smallest dimension of a non-circular opening such as a square, triangle or rectangle.

Considerable differences between actual performance and quoted ratings may also occur because of the differences between service and test conditions. Practical tests to establish ratings are normally conducted with high concentrations of suspended particles, which will tend to yield a higher filter efficiency because of the filter cake effect. Many tests, in fact, may be conducted under near clogged conditions of the filter, whereas, in practice, the filter may be operating for long periods with relatively clean fluids and in a lightly loaded state, when its efficiency is that much lower. A true absolute rating is necessary to enable prediction of filtration performance under these conditions.

Nominal rating

A *nominal rating* is an arbitrary value for the performance of a filter, determined by the filter manufacturer, and expressed in terms of percentage retention of a specified contaminant (usually spherical glass beads) of a given size. It also represents a nominal efficiency figure for the filter. Figures typically quoted are at the level of 90, 95 or 98% retention of the specified particle size. Many filter manufacturers use such tests, but the lack of uniformity and reproducibility has caused this measure to fall into disfavour.

The variations can be quite large. For example, a felt element with a nominal rating given as 30 μm may well pass 20–40% of particles of this size. At the same time, it may well retain a significant proportion of much smaller particles. This retention of undersize will, of course, always occur, the actual amount depending upon the design of the element.

Mean filter rating

A mean filter rating is a measurement of the mean pore size of a filter element. It is far more meaningful than a nominal filter rating, and, in the case of filter elements with varying pore sizes, more realistic than an absolute rating. It establishes the particle size above which the filter starts to be effective, and is relatively easily determined by means of the bubble point test described in the next Chapter.

Beta ratio

The *beta ratio* is a rating system introduced with the object of giving both filter manufacturer and filter user an accurate and representative comparison among various filter media. It is the ratio between the number of particles per unit volume above a specific size in the suspension upstream of the filter to the same parameter in the flow downstream of the filter, and it is determined in a test rig that enables accurate particle counting in the two flow regions. The beta ratio is then:

$$\beta_x = \mathrm{N}_u/\mathrm{N}_d$$

where: β_x is the beta ratio for particles larger than x μm, N_u is the number of particles per unit volume larger then x μm upstream, N_d is the number of particles per unit volume larger then x μm downstream.

It follows that the higher the value of the beta ratio, the more particles of the specified size, or greater, are retained on the filter. The filter efficiency at this particle size can then be determined from the beta ratio:

$$\mathrm{E}_x = 100(\beta_x - 1)/\beta_x$$

The beta ratio and the corresponding efficiency are illustrated in Table 1.5 in a test where the filter was challenged with 1 million particles per unit volume (the numbers in Table 1.5 refer, of course, to the same particle size).

Table 1.5 Beta ratio and efficiency

Beta ratio	Efficiency (%)	Downstream count
1.0	0	1,000,000
1.5	33	670,000
2.0	50	500,000
10	90	100,000
20	95	50,000
50	98	20,000
75	98.7	13,000
100	99	10,000
200	99.5	5000
1000	99.9	1000
10,000	99.99	100

Filter efficiency

The nominal rating of a filter can be expressed by means of this efficiency figure. Given as a percentage, it can be calculated from the beta ratio, or directly from the particle number count:

$$E_x = 100\,(N_u - N_d)/N_u$$

specific to a particular particle size. It applies over the whole particle size range, down to the absolute cut-off value, at which point the number of emergent particles should be zero, and the efficiency 100%. At any particle size level smaller than the absolute cut-off the efficiency must necessarily be less than 100%.

The classic method of determining filter efficiency is by the bead challenge test, with a rating expressed as a beta ratio, thus a beta ratio $\beta_x > 75$ specifies a filter efficiency of 98.6% or better relative to a particle size of x µm.

Microbial rating

One especially important case of purification concerns the removal of microbial contaminants so as to produce a sterile fluid. The use of membranes of 0.2 µm rating is generally regarded in critical industries as a satisfactory means of achieving sterility, demonstrated by a bacterial challenge test (NB this is referring to sterility from bacteria, not from viruses, which are much smaller than 0.2 µm). A typical challenge test uses *Pseudomonas diminuta* as the microbe with which to challenge the filter.

A standard means of expressing the microbial rating of a filter is by means of the Log Reduction Value. This is defined as the logarithm (to base 10) of the ratio of the total number of bacteria in the challenge suspension to the corresponding number in the filtered fluid, when the filter is subjected to a specific challenge. Generally a filter is considered suitable for sterilizing use if its output is free of bacteria in a challenge of 1×10^7 organisms per cm^2 of effective filter area (EFA). The concept of LRV can of course be applied to filtration other than at 0.2 µm (or indeed to other kinds of separation), provided that the test is then undertaken with the natural bioburden of the fluid, or with a bacterium of the appropriate size.

As an example of an LRV calculation, consider a standard 293 mm diameter disc of membrane, mounted in a membrane holder, providing an EFA of 468 cm^2. This is then challenged with a bacterial suspension equivalent to 1×10^7 organisms/cm^2, and is assumed to produce a sterile filtrate, i.e. one free of bacteria. The total number of organisms in the challenge is $468 \times 1 \times 10^7$, or 4.68×10^9.

The required ratio is: number of organisms in challenge/number in filtrate. By definition, the number in the filtrate is zero, but that would make this ratio infinitely large, so it is customary to enter a 1 for this term. The ratio then becomes 4.68×10^9, of which the logarithm is 9.67, and the LRV is then said to be greater than 9.67.

Filter permeability

The permeability is the reciprocal of the resistance to flow offered by the filter – thus, high permeability represents a low resistance and *vice versa*. Permeability is usually expressed in terms of a permeability coefficient, which is directly proportional to the product of flow rate, fluid viscosity and filter medium thickness, and inversely proportional to the product of filter area and fluid density, which gives the permeability coefficient the dimension of a length.

Such a derivation is cumbersome, and permeability behaviour is better expressed by a series of curves relating pressure drop across the filter medium with flow rate of the fluid through it. A separate series of pressure drop curves can be set up with respect to:

- filter size (i.e. filtration area)
- fluid temperature, and
- filtration time (i.e. degree of contamination of the medium).

A typical set of curves for the relationship with filter size is given in Figure 1.9. For a given flow rate, an increase in filter area will reduce the pressure drop across the filter, because the amount of fluid flowing per unit of filtration area is decreased (pressure drop is inversely proportional to filter area). This leads to a standard method for the sizing of a filter, a combination of the process flow rate required and an acceptable pressure drop leading to the optimum area (although it should be noted that the pressure drop will increase with filtration time as the medium becomes clogged).

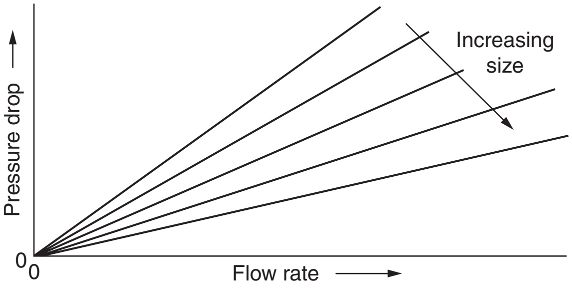


Figure 1.9 Filter size curves

If the medium thickness is increased at the same time as its area, then a different set of curves will be produced, because the medium also imposes a restriction on the flow of fluid. Each individual filter element will, therefore, have its own specific pressure drop-flow rate curve, depending upon its area, thickness and permeability.

The operating temperature of the fluid will affect the pressure drop across the filter because the fluid viscosity will change. A less viscous fluid will experience less resistance to flow through the medium, and so a lower pressure drop will be needed to drive it. As a result, pressure drop is inversely proportional to temperature, with a decrease in temperature causing a rise in pressure drop, as shown in Figure 1.10. A series of pressure drop *vs* flow rate curves at differing temperatures will thus establish the characteristics of a single filter over its working temperature range. (It should be noted that the temperature effect is much more pronounced for liquids than for gases.)

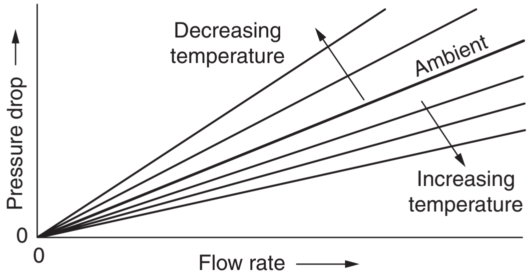


Figure 1.10 Effect of temperature change

An impact on fluid velocity is not the only potential effect of temperature change. At low temperatures, water contained in oil may freeze, causing blockage or at least partial blockage of the filter, and an abnormal rise in pressure drop. A similar effect occurs with waxes dissolved in an oil. These are changes that must be guarded against in an aircraft flying high, or a ship sailing into polar waters.

The effect of prolonged filtration time is to produce a cumulative build-up of collected solids on or in the filter medium, thus reducing permeability (and increasing flow resistance) in direct proportion to the amount of solid collected, as shown in Figure 1.11, which is another set of curves specific to an individual filter.

Characteristics expressed in the manner of Figure 1.11 are not particularly useful, because a practical filter will have been sized for a design flow rate, and this is then a

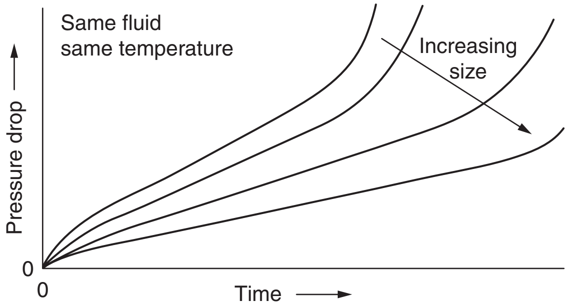


Figure 1.11 Effect of solid loading

working figure. It is more informative to plot the pressure drop across the filter as it changes with filtration time, to yield a single curve, as shown in Figure 1.12. The fact that this increase is caused by a build-up of contaminants is only a cause, and not an effect, although the load of contaminants retained by a filter during its working cycle can be significant as it may dictate the choice both of the type and of the size of the filter element.

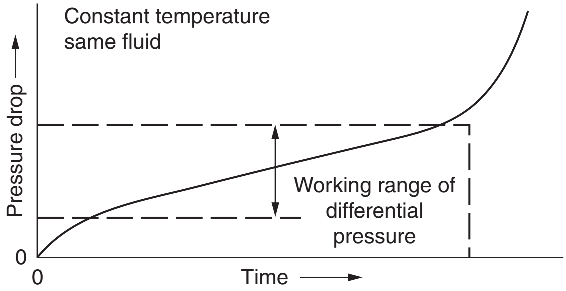


Figure 1.12 Pressure drop/time curve

The shape of the curve in Figure 1.12 is very typical: a fairly sharp initial rise, falling away to a prolonged linear growth section, which then curves up into a much steeper rise. The point at which this steeper rise begins is the time beyond which the filter will be too clogged for effective use – the efficiency will continue to increase with pressure drop, but the cost of operation becomes too high, and the element must be cleaned or changed.

The sharp increase in pressure drop can be used to indicate the need for the change, or it can cause the switch between an operating filter and its standby unit in a duplex housing.

Effect of pulsating flow

A steady flow of fluid through a filter will cause correspondingly steady accumulation of solids and rise in pressure drop. The effect of pulsating flow is to loosen the finer particles held in the filter cake, and so to allow them to pass through the filter and on into the filtrate. This effect is illustrated in Figure 1.13, which shows the higher particle counts downstream of the filter in pulsating flow, as compared with steady flow. This is another instance of the departure of the real filter system from the performance achieved with the same filter under laboratory conditions. Clearly, the likelihood of irregular flow must be allowed for in the initial selection process, such as choosing a finer filter from the start, in order to achieve the required filter efficiency.

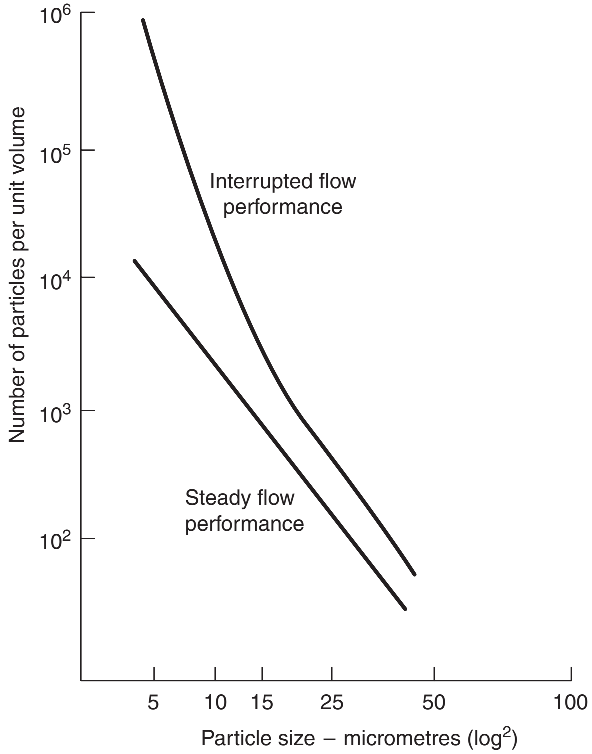


Figure 1.13 Steady and pulsating flow

1E. FILTER TESTS

A range of methods exists for testing various aspects of a filter's performance. These will be briefly discussed here, although a more complete review of test methods and standards is given in *Handbook of Filter Media* (Derek B. Purchas and Ken Sutherland, 2002, 2nd Edition, Elsevier Advanced Technology, Oxford).

Bead challenge test

The classic method of determining the absolute rating of a filter and its efficiency is by the bead challenge test, originally using spherical glass beads (ballotini), although a wide range of test materials is now available. In the test, beads of varying, but known, diameters are introduced in known concentrations and amounts to the feed flow to the filter under test. The filtrate is examined for the beads that have passed through the filter, and it is analysed in the appropriate way.

The simplest test is to look in the filtrate for the largest bead that can be found, whose diameter stipulates the absolute cut-off rating for the filter. A more thorough test involves a complete count of the particles in the filtrate by particle size, and the plotting of the results as percentage of the fed particles of a certain size passing through the filter against that size, in micrometres, as illustrated in Figure 1.14. This plot can then be used to establish the characteristics of the filter, showing, for example, the nominal rating in μm as the particle size at which $x\%$ of the fed beads of this size pass through the filter, i.e. at this size, the filter efficiency is $x\%$. Ratings are usually expressed at percentages passing between 10 and 2.

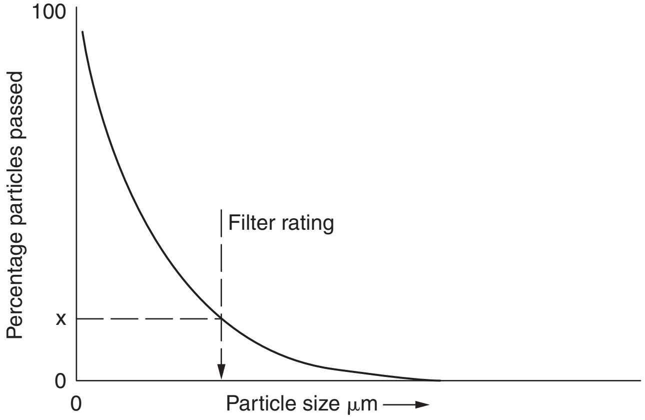


Figure 1.14 Filter efficiency

The efficiency of a filter describes its ability to guarantee the quality of the filtrate, and should be measured under conditions that most closely represent the real operating situation.

The true efficiency equation needs to take note of the presence of contaminants in the test fluid. On a count basis, this should be determined as:

$$\text{efficiency} = 100\{A - (B - C)\}/A$$

where: A = particle count added to the fluid upstream of the filter housing, B = particle count downstream of the filter element, and C = particle count downstream of the filter housing, but in the absence of a filter element.

The inclusion of the blank count, C, ensures that the actual number of particles incident upon the filter is properly measured. Such inclusion is particularly important where contaminant loadings are measured by weighing rather than counting.

The bead challenge test is time-consuming, and has considerable practical limitations where micrometre-sized beads are involved. Whilst the feed dosage can be counted by weighing, the segregation and counting of the particles in the filtrate is a very exacting task, as well as being subject to limitations such as the provision of accurate depth of focus and field of view in the microscope.

In addition to glass beads, various other forms of test particles are used in the counting test. Glass beads are mainly used in the size range 10 to 25 µm, while finer particles are available as sand (down to 0.25 µm) and iron oxide (down to 0.5 µm). A very wide range of test dusts is available for air filter testing (in the range 1 to 100 µm), while di-octyl phthalate (DOP) is also used for the evaluation of air filters, with a particle size of about 0.3 µm.

Maximum particle passed test

A specific test method exists to measure the size of the largest hard, spherical particle passed by a filter, and hence determine its absolute rating. The test rig is illustrated schematically in Figure 1.15, much of which is included to provide a clean basis for the test. Thus the fluid is first circulated through a clean-up filter until a sample shows

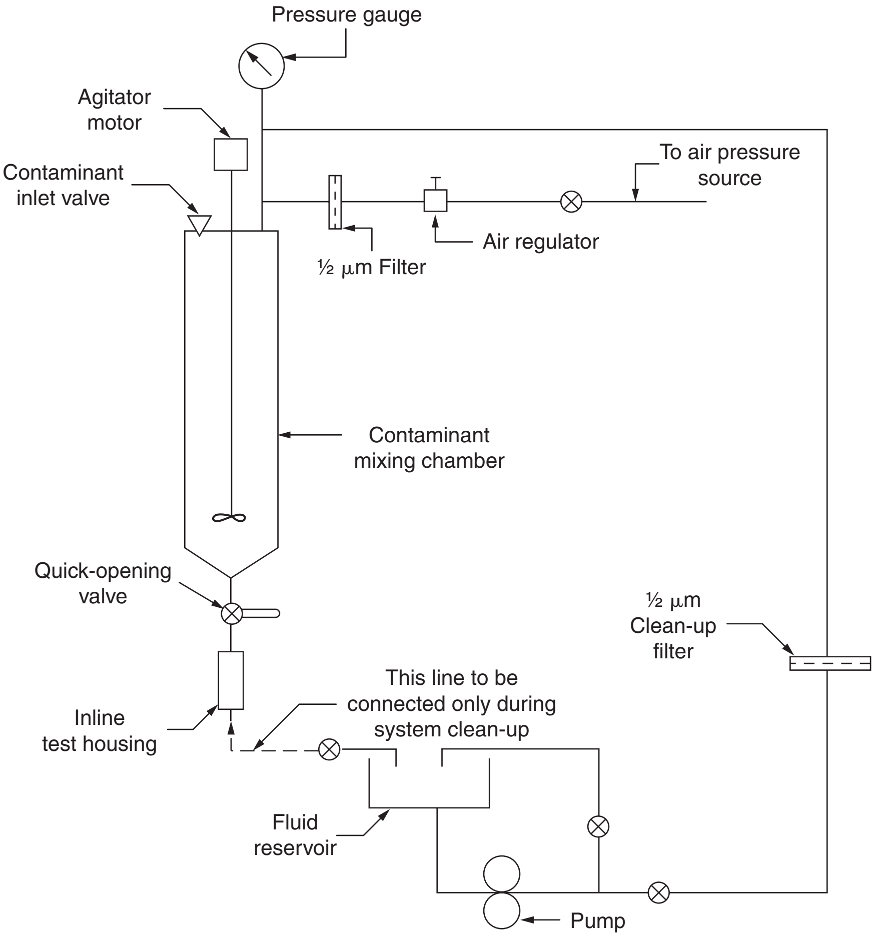


Figure 1.15 Maximum particle passed test rig

a cleanliness level of 0.4 mg/100 ml, by gravimetric analysis. A measured quantity of artificial contaminant in graded sizes (usually glass beads in the size range 2–80 μm) is then introduced into the mixing chamber. After sufficient agitation, a measured volume of the resultant suspension is passed through the test filter housing and collected in a beaker. This filtrate is then passed through a very fine membrane filter, to remove and collect all of the suspended particles from that filtrate sample. The solids on the membrane surface are then examined through a high-powered microscope, to find the largest particle present in the filtrate, so giving the absolute rating of the filter.

Degree of filtration test

The degree of filtration is determined in apparatus very similar to that of Figure 1.15, except that the weight of contaminant added is measured, as is the weight of particles passing through in the filtrate. The degree of filtration is then determined as:

$$100(W_1 - W_2)/W_1$$

where: W_1 = weight of added contaminant, and W_2 = weight of filtrate solids collected on the membrane filter.

This calculated figure also establishes a nominal rating for the filter, relative to the specified contaminant.

Multi-pass test

The multi-pass test is intended specifically to determine the beta ratio, as described in Section 1D; for example, for filters used in hydraulic and lubrication systems. The principle of the test rig is shown in Figure 1.16, in which a fluid carrying a specific load of particles, of known size and number composition, is continuously circulated around a loop through a test filter housing with its sample points. Additional suspension is continually fed into the circulating flow to maintain a constant flow of contaminants into the test filter, making up for the particles lost through being trapped in the filter, and for the fluid removed from the system as samples. These samples are withdrawn simultaneously from upstream and downstream of the filter, at predetermined levels of the pressure drop across the test filter, and are analysed in an automatic particle counter. The contaminant will be a standard test dust, such as ISO Medium Test Dust for the hydraulic and lubricating systems suggested.

From the counted samples, the cumulative particle size distribution in unit volume of the fluid is then determined, over a range of sizes to match the fed dust (such as 5, 10, 20, 30 and 40 μm). The beta ratio can then be calculated for each of the selected particle sizes (as in Section 1D) from:

$$\beta_x = N_u/N_d$$

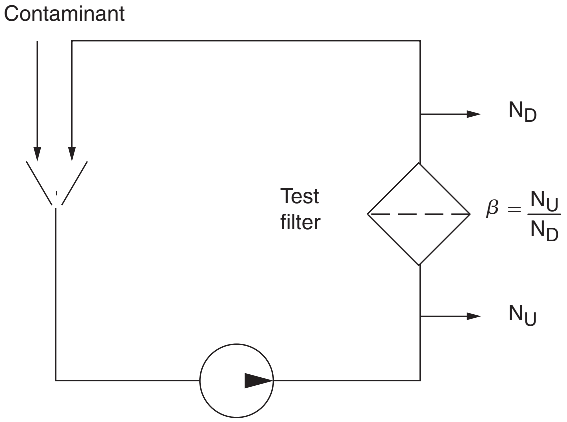


Figure 1.16 Multi-pass test principle

with the corresponding efficiency as:

$$E_x = 100(\beta_x - 1)/\beta_x$$

again, for the specific particle size.

The multi-pass test simulates well the behaviour of clarifying filters in hydraulic or lubricating fluid systems, because the recycle of the filtrate carries with it the undersized particles, so that the proportion of fine particles increases continuously during the test. It was the first filter test to become an ANSI standard, and is now incorporated into an international standard (see BS ISO 16889:1999). It should be noted that the beta ratio will be different from that determined by this test if it is used in a system that contains particle distributions that differ from the distribution used in the test.

Many filter elements exhibit beta ratios that degrade significantly as pressure drops increase. A multi-pass test must therefore be run to a terminal pressure drop that is higher than the operational setting of the dirty element warning device in say a real hydraulic system, to obtain realistic beta ratios for the entire expected life of the filter. It is thus necessary, when a hydraulic filter is being selected, to compare the plot of the beta ratio against differential pressure from the clean element pressure drop all the way through to terminal pressure drop, and to compare this plot with the settings of the dirty element alarm and any bypass valve.

Single-pass test

As its name implies, the single-pass test feeds a constant flow of suspension to a filter, but does not recycle the filtrate, as illustrated in Figure 1.17. The filtrate is

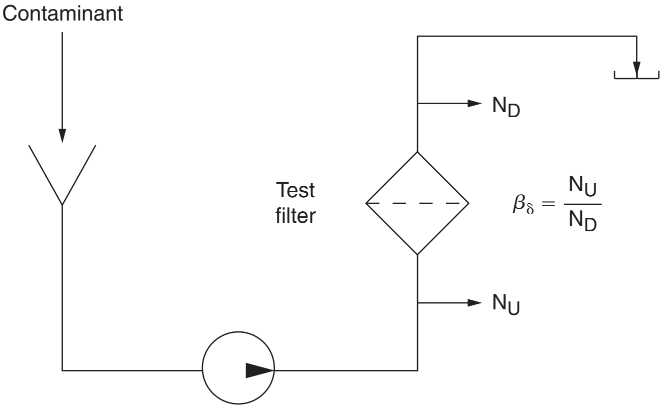


Figure 1.17 Single-pass test principle

collected in a separate receiver, and solids trapped in the test filter are allowed to accumulate, with a corresponding rise in the differential pressure across the filter. Simultaneous samples of feed and filtrate are made and particle counts obtained as with the multi-pass test, and the beta ratio and efficiency figures are calculated in the same way.

The single-pass test thus presents the test filter with an unchanging feed composition, which more closely duplicates the majority of filtration processes, which have relatively unaltered feed during operation. In this test, changes in filter performance are reflected by changes in the downstream conditions. It is possible, with this test, to show more easily the effect of important variables on filter performance. One of these is the ability of a filter element to hold sufficient solid contaminants without the development of an unacceptable pressure drop – the retention capacity of a filter element is easily determined in a single-pass test.

Companies offering testing services, such as IFTS in France, or Palas in Germany, have fully automated test rigs, able to carry out single and multi-pass tests quickly and accurately.

Bubble point test

The tests described so far have all been challenge tests, in which a known suspension is fed to a test filter. The bubble point test, on the other hand, measures a characteristic of the filter medium without use of particles.

The bubble point test is based on the fact that, for a porous filter medium, immersed in and thoroughly wetted by a specific liquid, the pressure required to force a gas bubble through a pore is inversely proportional to the diameter of the pore. In practice, this means that the pore size of a filter element can be established by wetting the element completely with the liquid and measuring the pressure at which the first stream of bubbles is emitted from the upper surface of the element when air pressure is applied to the underside.

A typical rig for the bubble point test is shown in Figure 1.18. The sample of filter medium is immersed in a suitable liquid (often *i*-propyl alcohol), and air is forced into the interior of the sample from a reservoir until the first bubble is seen, at which point the air pressure is recorded.

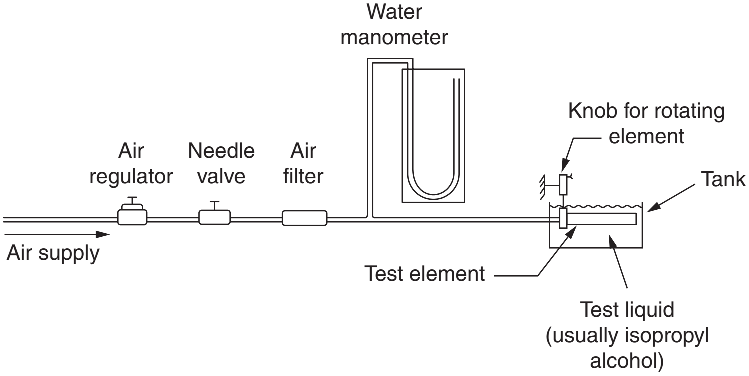


Figure 1.18 Bubble point test rig

The relationship between bubble point pressure and pore diameter derives from Poiseuille's law for capillary tubes:

$$P = (4\mathrm{r}.\cos\theta)/d$$

where: P = bubble point pressure, r = surface tension of the liquid, which must wet the capillary wall, θ = angle of contact between wall and wetting liquid, and d = pore diameter.

As no real pore is absolutely capillary in shape, it becomes necessary to introduce an empirical constant into this relationship:

$$P = (4\mathrm{Kr}.\cos\theta)/d$$

In a given liquid/material combination, r and θ are effectively constant, so that the relationship becomes:

$$P = \mathrm{K}'/d$$

with K′ as another empirical constant dependent upon the nature of the liquid and filter material, and on the form of the units employed in the equation.

In the test procedure, the point on the sample from which the first bubbles appear marks the place of the largest pore. A further increase in pressure will produce a second stream of bubbles, from the second largest hole, then the third, and so on. Eventually a pressure is reached at which bubbles will appear to come from the entire surface of the element. This pressure is known as the *open bubble* or *boil point*, and is a reasonable measure of the mean pore size of the element. This latter figure is to some extent dependent upon the air velocity through the pores, so comparative tests on different materials should be carried out at the same flow rate (air velocity does not affect the value of the initial bubble point).

In an instrumented form of test rig, a sample of the filter medium, saturated with liquid, is placed in the sample holder, forming a seal between the bottom of the sample chamber and the atmosphere. Gas (usually air) is injected into the space under the sample at a controlled rate causing the pressure in the chamber to increase. When the applied pressure is high enough to force the liquid from the largest pore, it will stop increasing momentarily, which will signal the recorder to note the applied pressure, the bubble point.

A particular advantage of the bubble point test is that it is non-destructive, i.e. it does not damage nor contaminate the filter element. It can thus be used as the basis for a method of testing the integrity of the filter, i.e. for demonstrating that there are no holes that should not be there, in the body of the filter medium or at its perimeter. The test can also be correlated to bead challenge tests, and combined with a maximum particle passed test, can be used to determine K or K' for different designs of filter element using the same medium.

A comparable procedure can be built into a capillary flow porometer, which will enable the carrying out of bubble point, pore distribution, capillary flow and gas permeability determinations.

Dirt capacity test

It has already been mentioned that the single-pass flow test is capable of determining the ability of the filter medium to hold accumulated dirt on or within the medium. A rather more complicated rig for this purpose is shown in Figure 1.19, which can be used for determining the lifetime of the filter element, in terms of the maximum acceptable pressure drop across the element, as determined by the amount of solid accumulated in or on it. In the system shown in Figure 1.19, a continuous flow of suspension is maintained through the test element. A specified amount of contaminant is added to the flow upstream of the element at regular time intervals, and the differential pressure across the element is recorded, so that a graph may be drawn of contaminant added *vs* pressure drop. It will be possible to specify the maximum pressure drop that will be acceptable across the element (in terms of fluid pumping energy), and therefore the maximum solid accumulation permitted – and hence the time between element changes.

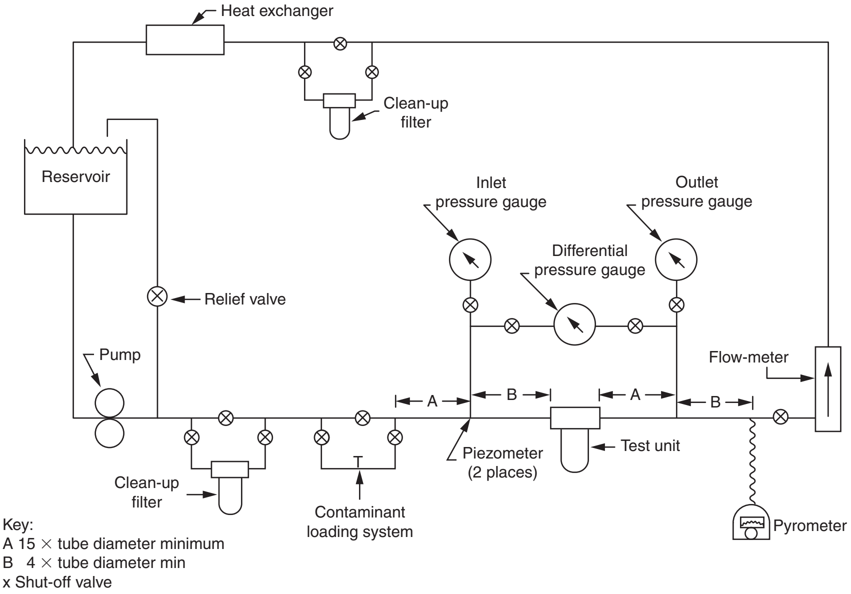


Figure 1.19 Dirt capacity test rig

Clean pressure drop test

In the same, or a similar, rig to that of Figure 1.19, but without the addition of contaminant solid, the clean fluid is circulated at measured flow rates and controlled temperatures. A plot can then be drawn of the clean element pressure drop against fluid flow rate. This can be done first in the absence of the element, to determine the resistance of the filter housing alone, followed by that of the combined element and housing. It may be possible to check the behaviour of the element alone, from which it may be found that the drop across element and housing may not be the exact sum of the two separately.

Collapse test

A continuation of the pressure drop test, now using contaminated fluid, at the flow rate expected for the filter in use, will allow the differential pressure to rise (given a pump capable of achieving the differentials) to the point where the element is caused to fail or collapse.

Media migration test

In any filtration process, but especially in clarifying processes designed to produce a clean filtrate, it obviously must not be possible for fragments of the filter medium to fall off the element and so contaminate the filtrate. A rig suitable for checking on migration behaviour is similar to that used for the maximum particle passing test (i.e. Figure 1.15), now only with clean fluid passing continuously through the test sample, so that the only contaminants collecting on the membrane filter are those that have migrated from the sample. Loss rates can be plotted against time and flow rate.

Migration tests should, as necessary, be modified to simulate actual service conditions, including other parameters such as fluctuating flow, flow reversal and mechanical vibration.

Fatigue tests

The test circuit used for fatigue tests subjects the filter to start-stop cycles (for evaluating fatigue behaviour under otherwise steady flow conditions), or to cycles of pressure fluctuation (for evaluation of fatigue under pulsating flow conditions). A bubble point test applied to the filter element before the fatigue test, and again after it, will demonstrate the integrity of the filter.

Acceptable figures for cycle life before failure can vary widely with different types of filter element, but as a general guide they are of the order of 10,000 cycles for steady flow operation, and anywhere from 100,000 to 1,250,000 cycles for pulsating flow.

Air filter tests

All gas phase filter tests are of the single-pass format using a particle challenge, but the methods differ widely, as do the particle formulations used in the challenge and the means of analysis to demonstrate performance. The materials used include natural sand/quartz mixtures, alumina dusts, methylene blue aerosols and di-octyl phthalate. A sand-quartz mix is specified for the valuation of air filters for IC engines and compressors, originally in BS 1701, now BS ISO 5011.

Alumina dusts, such as Aloxite 50 and 225, are specified for ventilation filter testing, originally in BS 2831, then BS 6540, and now BS EN 779. The particle size distributions for these two dusts are shown in Figure 1.20 in a form common for size distribution illustration, i.e. the percentage below a particular particle size in the mixture, plotted against particle size.

An aerosol of methylene blue dye is used primarily for the testing of low penetration filters. The particles are extremely fine, with an average size around 0.5 μm and no particles above 1.3 μm, as shown in Table 1.6. This challenge material would not be used for testing ordinary air-conditioning filters, as these would show a low efficiency with this material. The test technique involves the atomization of a methylene blue dye solution through a spray nozzle at a specified pressure, discharging the spray into a duct that houses the filter under test. Sampling points are located upstream and downstream of the filter, in straight sections of duct. The upstream section is of sufficient length to allow moisture to evaporate from the droplets of dye, leaving a dust cloud of dispersed methylene blue particles.

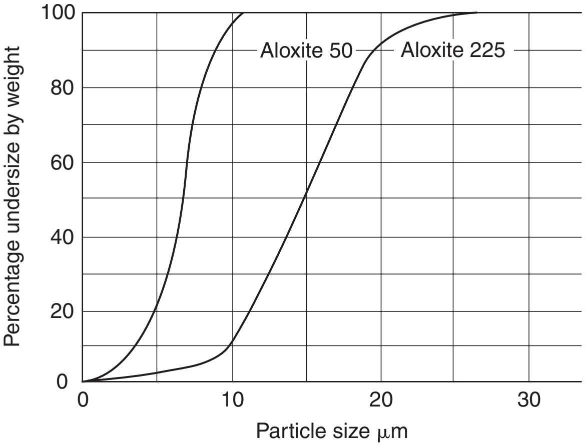


Figure 1.20 Alumina particle size distributions

Table 1.6 Methylene blue particle size distribution

Size (μm)	Percentage undersize by number	Percentage undersize by weight
0.011	16.5	0.006
0.032	36.0	0.08
0.065	56.5	1.17
0.130	81.0	8.66
0.216	92.5	19.7
0.305	96.8	31.0
0.390	98.2	41.5
0.475	99.0	53.2
0.610	99.5	74.2
0.785	99.8	91.7
1.130	99.9	97.5
1.300	100.0	100.0

The performance of the filter is then assessed by comparing stain samples taken on either side of the element.

A technique that is somewhat easier to use is the sodium flame test, which produces an aerosol of sodium chloride particles, as with methylene blue, but assesses the dust content of the air upstream and downstream of the filter by the intensity of the yellow colour produced by the salt dust in a hydrogen flame (BS 3928). The size distribution of the salt dust is shown in Table 1.7, with a mean size around 0.6 μm, and no particle larger than 1.7 μm. The colour of the flame is observed by a photosensitive cell connected to a meter, which can be calibrated to read the salt concentration directly.

Table 1.7 Salt cloud particle size distribution

Size (μm)	Percentage undersize
0.1	58.0
0.2	55.0
0.3	93.5
0.4	96.7
0.5	98.2
0.6	99.0
0.7	99.45
0.8	99.65
0.9	99.80
1.0	99.87
1.1	99.91
1.2	99.94
1.3	99.96
1.4	99.97
1.5	99.98
1.6	99.99
1.7	100.0

Di-octyl phthalate aerosols are also widely used for penetration tests – they differ by being aerosols of liquid droplets at the test filter, and by being a mono-disperse aerosol (i.e. all of one particle size, 0.3 μm). Such tests are recognized as suitable for HEPA filters.

There are three main types of air filter test (in addition to the sodium flame test):

- staining tests (as with methylene blue)
- weight arrestance, and
- particle concentration efficiency.

The determination of atmospheric dust spot efficiency is a staining test, described in detail in BS EN 779, and used for AC and ventilation filters. It is based on the intensity of staining of a target ultrafine filter paper caused by the flow through it of a quantity of dusty air. The intensity of staining is measured by an opacity meter, and provides an empirical measurement of the concentration of contaminant in the air stream. In the filter test, the downstream air flows constantly through its collection paper, while the upstream air is sampled for only a proportion of the time (because of its much higher dust concentration), and this proportion is controlled to yield an equivalent stain to that from the downstream flow. The flow ratio can then be converted to a filtration efficiency.

The dust weight arrestance test is equivalent to the single-pass flow test described earlier. The test filter is challenged with a weighed quantity of a test dust, the filtrate passing on through a second very fine filter, which captures all of the dust passing through the test unit. The amount of dust passing is determined by weighing the final filter. The feed dust suspension is created continuously by a suitable combination of a dust feeder and a compressed air venturi ejector, blowing the dust into the feed air stream. As the test progresses, the weight of dust passing and the corresponding pressure drop are continually measured.

The particle concentration efficiency tests are used for the various grades of high efficiency air filters (HEPA, ULPA), and use the sub-micrometre aerosols described in earlier paragraphs. The procedures are described in detail in BS EN 1822, which also highlights the Most Penetrating Particle Size (MPPS) as probably the most important performance characteristic.

Membrane characterization

The assessment of the filtration characteristics of membranes is in principle no different from that of other fine liquid filters, but in practice is more difficult, because of the very fine degrees of filtration involved. Description of the characterization processes is covered under the Membrane chapter of Section 2.

2

FILTER MEDIA

SECTION CONTENTS

2A. INTRODUCTION

The Elsevier *Handbook of Filter Media* has a precise definition of a filter medium:

> *A filter medium is any material that, under the operating conditions of the filter, is permeable to one or more components of a mixture, solution or suspension, and is impermeable to the remaining components.*

The retained components, the ones to which the medium is impermeable, may be particles of solid, droplets of liquid, colloidal material, or molecular or ionic species in solution, while the permeate (or filtrate) will normally be the suspending fluid or solvent, possibly together with some of the other components. (Note: this definition includes the diffusion processes of reverse osmosis and nanofiltration, which are not strictly filtration processes, because of their similarity to membrane ultrafiltration and microfiltration, which are.)

It is true to say that any material that is porous or can be rendered porous or made into a porous structure, whether the pores are the size of a person's fist or smaller than a micrometre, can serve as a filter medium. However, as far as is reasonable, a filter medium should be strong (in tension at least), flexible, resistant to corrosion and abrasion, easily manipulated into the required shapes and capable of being made with a range of porosities. These requirements cut down on the number of possible media, but still leave plenty of potential materials: inorganic (minerals, carbon, glass, metals and metal oxides/ceramics), and organic (natural and synthetic).

Each of these basic materials lends itself to one or more formats of filter media, as shown in Table 2.1, which gives the media formats for each of the materials from

Table 2.1 Types of filter media by material

Material	Format
Natural fibre: wool, cotton, etc.	Felt: loose, bonded, needled
Natural filament: silk	Woven yarn, filament
	Knitted yarn, filament
	Wound yarn
Processed natural fibre: cellulose	Wet-laid (paper, filter sheets)
Man-made organic: regenerated cellulose	Granules: loose, bonded, sintered
synthetic polymers	Fibres and Filaments: felted, woven, dry-laid (spun), wet-laid (paper), rigidized, sintered
	Foam
	Extruded mesh ('Netlon')
	Sheet: perforated, stretched (fibrillated), porous, membrane
	Tubular: rigid porous, hollow fibre
Metals: ferrous and non-ferrous	Rod or bar structures
	Granules or powder: loose, sintered
	Fibres: loose, sintered
	Sheets: perforated (punched, etched)
	Wire: wound cartridge, woven mesh, sintered mesh
	Expanded mesh ('Expamet')
	Foam
Glass	Fibre: wet-laid (paper)
	Porous tube
Carbon: natural	Granules or powder: loose, bonded, embedded
activated	Fibres: loose, felted, woven, embedded
	Porous block
Ceramics: metal oxides	Granules or powder: loose, sintered
others	Formed blocks, with tubular holes
	Fibres: loose, sintered
	Foam
Other minerals: mineral wools	Fibres: wet-laid (filter sheets), pads
sand, anthracite, garnet	Granules
Various materials (metal, paper, plastic)	Solid fabrications: stacked discs, edge filters, wedge wire, wire wound
Paper-like materials	Pleated sheet
Inert granules of all kinds	Packed beds (deep bed filters)
Mixtures of inert and active materials	Combination media

which media can be made. A variant of this information is given in Table 2.2, relating material form to the types of media in that format.

Table 2.2 Filter media types by format

Basic media format	Types of media
Loose granules	Deep bed
Loose fibres	Pads, felts
Structured granules	Bonded, sintered
Structured fibre	Needlefelts, bonded, wet-laid (paper) spun (spun bonded, melt blown)
Sheet	Perforated, microporous (including membrane)
Woven/knitted	Spun yarn, monofilament (including wire)
Tubular	Rigid porous, hollow fibre/capillary
Block	Rigid (with interior channels), foam
Wound on core	Spun yarn, monofilament (including wire)
Structured array	Ribbon, stacked discs, rod and bar structures
Extruded mesh	'Netlon' type

This Section describes filter media in general terms. More detail is available in *Handbook of Filter Media* (Derek B. Purchas and Ken Sutherland, 2002, 2nd Edition, Elsevier Advanced Technology, Oxford).

The filter media business

The industrial context within which filter media are made and supplied to their end-users is of more than passing interest. The great variety in which media are made leads to a corresponding variety in the types of company involved with the supply of media. Some are devoted to its manufacture, while for others it may be only a small part of the total company activity.

Five main stages can be seen in the industry. These are the:

1. maker of the basic material from which the medium is to be made: a metal wire, a natural or synthetic fibre, a ceramic powder, an extruded plastic filament, and so on
2. conversion of some of these basic materials into a form in which they can be used to make filter media: the spinning of fibres or the twisting of filaments into a yarn, the crimping of a wire, etc.
3. formation of the bulk medium: the weaving of a cloth or monofilament mesh, the moulding and sintering of a mass of plastic or metal fibre or powder, the production of paper, the preparation and processing of a sheet of membrane (all together with any necessary finishing processes)
4. conversion of the bulk medium material into pieces of the particular size and shape required for the medium to fit the filter (especially for makers of replacement

media for existing filter units), which may include, for example, the pleating of flat material
5. making of the filter itself, including the fitting or adapting of the medium to its position in the filter.

A sixth stage – the distributor or wholesaler – frequently stands at the end of this process, serving the end-user, and may exist at several inter-stage points in this series. The creation of a stand-alone filter element, such as a cartridge, might be considered as part of stage iv, or as a further stage between stages iv and v – and then bypassing stage v, by direct sale to the end-user.

Many companies in the industry exhibit combinations of two or more of these manufacturing stages (vertical integration), but this may result in limitation of the markets for the products of the earlier stage.

Some media, of course, do not exhibit all these stages: sand filters go from the supplier of the graded sand straight to the deep bed filter maker. Most, however, show several, with some of the most common (woven fabrics, needle felts) exhibiting all of them. This complicated market structure obviously has its impact on a review of this nature – which basically looks only at the products of stages iii and iv.

The filter media business is a large one. It is estimated that the global market for media of all kinds will be about $21 billions in 2007, and is growing at about 5.5% per year. This market value is counted after stage iv in the above manufacturing chain, i.e. at the point where the finished filter medium is about to be inserted into a filter. The costs of filter media vary extremely widely even within one type, let alone among the different types, as is shown in Table 2.3.

Table 2.3 Costs of some filter media

Filter media type	Cost range, £/m^2
Papers	0.15–0.25
Spunbonded fibres	0.05–5
Needle felts	4–7
Woven polypropylene	4–6
Woven cotton	5–7.5
Woven wire mesh	35–200
Microfiltration membranes	60–500
Porous ceramics	200–300
Five-layer sintered wire mesh	700–1200

2B. ABSORBENT, ADSORBENT AND BIOLOGICAL FILTER MEDIA

First to be considered in this review of filter media are three types of material whose prime function is *not* the separation of solid particles from fluids, but in whose use such separation does occur. They operate by different physical processes from filtration (and from each other), and are used for different purposes.

Absorbent media

An absorbent material is akin to a sponge in that it can draw fluid into itself and retain this fluid within its structure, and the fluid can only then desorb by a change in phase (such as evaporation or drying). In this sense, it can act as a filter by removing liquid droplets, for example, provided that they wet the absorbent. Thus, an untreated paper, being an absorbent material, could filter out water droplets from an air stream. However, its usefulness as a practical filter in such a case would be very limited, both as regards to retention of moisture, as it would soon achieve the maximum possible absorption capacity, and to mechanical strength, as it will be weakened by the moisture content (which may also act as a solvent for any binder in the paper).

Increased wet strength can be achieved for papers by impregnation with substances like neoprene, or phenol formaldehyde and other synthetic resins. However, the impregnation lowers the absorption capacity, and it is more often the case that papers for use as filters are specially treated to make them non-absorbent, to provide maximum mechanical strength and resistance to solvent action.

Natural fibres, such as wool and cotton, and the felts made from them, are also absorbent materials, but the use of such absorbent media purely as absorbent filters is very limited. These materials are widely used as filter media, with their absorptive properties of secondary or negligible significance.

Adsorbent media

It has been stated in Section 1C that the fundamental method of entrapment of a particle from a fluid by a filter medium is an adsorptive process, but it is a different adsorption system that is being referred to here, namely the removal from a fluid (liquid or gas) of a fluid component that is intimately mixed with it. The adsorption process occurs at the surface of a solid material, whose surface area should therefore be as large as possible, and happens because of electrical attraction at the molecular level. Specific types of material, normally in the form of finely divided granular or powdered solids, can exhibit high adsorptive properties when in contact with vapours and non-solid contaminants present in fluids.

If such granules can be suitably contained (for example, in a packed bed or column), they will also act as a mechanical depth filter, trapping the suspended particles within the bed. Adsorbent filters can also be made by the addition of adsorbent solids to a normal piece of filter medium, either as a layer sandwiched between two sheets of medium, or by embedding particles of adsorbent in the material of the filter medium, to make what is called a combination medium.

The chief adsorptive medium used is granular or powdered carbon that has been activated by steam or chemical treatment to create a porous structure with very high surface area per unit weight of carbon. Fuller's earth, a naturally active clay, is also used as an adsorbent.

Adsorbent media are widely used for the removal of odours, smoke, fumes etc., in a wide range of applications from domestic (e.g. kitchen cooker-hood filters) through to air-conditioning plants and to industrial fume removal. Activated carbon is also the filter medium normally used for water purifying or clarifying on small-scale applications such as drinking water supplies in caravans or boats. Industrially, adsorbent filters are used for the removal of odours from oils, and of odours and tastes from foodstuffs and beverages. The adsorbent properties of the medium means that it removes dissolved as well as undissolved contaminants, the medium being chosen accordingly.

An important development in activated carbon formats is the production of charcoal cloth as a quite distinct form of the material, first developed in 1977. It has a high adsorption capacity and has the distinct advantage of being strong and flexible, with good resistance to shock and vibration, and hence it can provide a self supporting filter element. It is manufactured from pretreated woven cellulose fibre cloth, reduced to 100% carbon in a controlled atmosphere furnace, maintained so as to ensure the desired strength and adsorptive capacity. The process reduces the cellulose cloth to a quarter of its original weight, yielding an activated charcoal cloth with high porosity and high surface area. Although expensive to produce, charcoal cloth has special applications such as respirators and gas masks.

Biological filters

There is another group of equipment to which the word ‘filter’ is attached in their name that have a prime function that is not the act of filtration, but in which filtration does play a part. These are the biological or trickle filters much used in the processing of water and wastewater. They consist of a packed bed of coarse granules or pieces of plastic over which the water to be treated is allowed to run. The purification takes place in a layer of biological material that forms on the surface of the packing. A certain amount of filtration of suspended solids does take place by adhesion to the packing, but the digestion process also produces solids that are swept out in the effluent stream and so these types of equipment do not clarify the feed from suspended solids so much as remove dissolved organic material from solution in the liquid.

2C. PAPER AND FABRICS

The previous part of this Section covered processes that dealt with filtration in a minor way, but which were not primarily intended for the separation of particles from fluids. The majority of the Section is now concerned with those materials intended for filtration and will describe them in sufficient detail to explain how they are used and their main advantages. This first topic of the group of filtration media deals with those materials that are based on fibres of various kinds, short or long, spun into a yarn or laid down individually to create a random mass.

These fibres may come from natural sources such as wool or cotton, or the basic cellulose of wood, or they may be synthetic, produced by the extrusion of a molten polymer, which means that they are probably produced initially as a continuous filament and then broken up to form the required length of fibre. This appears to imply that such materials are organic in origin, but modern manufacturing techniques enable almost any inorganic material to be produced as fine fibres: carbon, glass, metals and ceramics, and so as a yarn or pad of randomly oriented fibres.

The properties of the finished fibrous material as a filter medium are then very much related to the properties of the fibres or filaments themselves, the most important correlation being that of size: the finer the fibre from which the material is made, the finer the particle that will be trapped by the resultant filter medium. The selection of a fine fibre from which to make a particular filter medium must be made in the realization that the finer fibres will produce a less strong material. The fibre choice then becomes an optimization exercise among degree of filtration (cut-point and efficiency), pressure drop (i.e. energy consumption in operation) and mechanical strength. A weak material, but one with the required filtration performance, can be strengthened by supporting it on a stronger substrate – but at an increase in cost per unit of filtration area.

It is not unusual that a filter medium is over-specified, and consequently costs more than it need do. As seen in Section 1A, some filter media are extremely expensive, and there would appear to be little point in purchasing a costly or technologically advanced medium, when there is a well tried, tested and less expensive alternative available.

Nevertheless, it is also true that the demands being made upon filters in terms of finer degrees of filtration are growing, and this will lead to a continual lowering of filtration cut-points and increasing filtration efficiencies, with as little increase in first cost or operating costs as possible.

Paper media

Paper is made by the wet laying of a mass of cellulose fibres onto a woven wire band, which is effectively a filter through which the water drains and the fibres settle down to produce a continuous sheet. A slurry of cellulose fibres, or pulp, is formed by disintegrating and beating (or chemically treating) wood chips, and is then slowly and evenly fed onto the woven wire. The fibres settle in a random manner to form the sheet of paper, which has to be pressed and dried to achieve the required moisture content.

The resultant porous sheet can be used as a filter medium, but if the untreated paper gets wet then the fibres absorb moisture, with two significant consequences: the fibres swell, so that the spaces between them reduce and the paper improves in filtration efficiency, but the mechanical strength drops sharply, making the paper less useful as a filter. To be used as a filter, then, the paper must be fully supported for use in wet filtration (as, for example, in the filter papers used in the laboratory filter funnel) or it must be restricted to dry filtration (such as in building air cleaning).

Alternatively, the paper must be treated with some sort of binder to give it intrinsic strength. The effect of an impregnated neoprene binder is shown in Figure 2.1, with a very significant increase in wet strength for a small amount of binder.

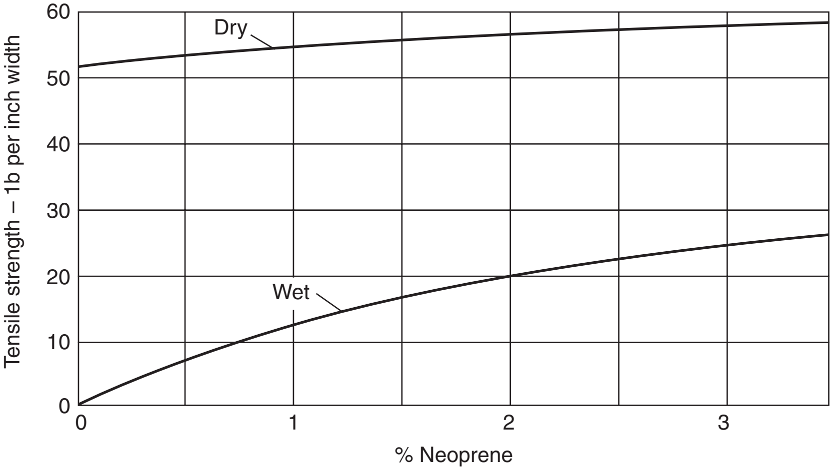


Figure 2.1 Effect of neoprene binder on filter paper strength

By the nature of their formation, papers have a random fibre structure, although this can be controlled to a large extent in the manufacturing process. They also have a relatively low permeability. Because of the tortuous nature of the flow path through the paper, only relatively thin sheets can be used for practical filtering, and even then the specific resistance is high. However, treated papers have two great advantages as filter media: they can be made with nominal cut-offs of 10–20 μm or better, able in practice to remove a high proportion of much finer particles; and they are quite inexpensive materials.

The chief disadvantages of paper media are their high specific resistance and their limited mechanical strength. To offset the former, paper filter elements are most commonly used in pleated form, considerably increasing the superficial area for a given size of element. This substantially reduces the flow velocity through the paper and hence the effective or overall resistance to flow. Pleating also improves the rigidity of the element, although it is normally fully supported by a perforated inner tube or core. The depth of pleating is usually of the order of one quarter of the diameter of the element.

Variations on the simple pleated form include corrugating the paper before pleating, which has the effect of increasing both the surface area and to some extent the stiffness; or dimpling the surface; or the attachment of separator strips to maintain constant spacing and prevent the collapse of the pleats. Collapse of a pleated element will reduce the effective surface area and, if excessive, may lead to tearing.

The mechanical strength limitations of paper elements normally set a maximum working pressure for such types at about 7 bar. This can be improved by rigid reinforcement, for example a wire mesh backing, but higher pressures also increase the chance of element migration (i.e. fibres breaking away from the paper sheet and leaving the filter as a contaminant in the filtrate). This is always a possibility with paper elements, especially if they become choked and the system does not incorporate a pressure relief valve to bypass the element.

Another inherent limitation with paper elements is that the very nature of the material does not provide an absolute cut-off point. There will almost certainly always be larger pore sizes than the nominal rating and so random larger particles may be passed by the filter. This limits the suitability of paper elements for ultra-fine filtering. On the other hand, the performance of paper, and particularly resin impregnated paper elements, can be superior in performance to other types of fabric media.

Although paper elements are invariably thin, they still have a finite thickness so that they filter in depth as well as acting as a simple mechanical screen. However contaminants will mostly collect on the outer surface, and the accumulation of such contaminants will progressively increase the efficiency of the filtration by acting as a filter cake.

The fact that some solid contaminants will tend to penetrate into the depths of the paper, and so become lodged there, can make cleaning difficult or even impractical. In the case of dry fluids, such as air, adequate cleaning may be provided by a back flow of air to blow the cake off the surface. Paper elements may then be reusable in such cases. With wet fluids, such as oil or water, it is more usual to employ disposable filter elements, which are simply replaced when they become clogged.

The progress of cellulose paper as a filter medium has been considerably affected by the manufacture of fibres of other materials that can be formed into paper-like sheets by adapting the conventional paper-making process; the outstanding example of this is the variety of glass fibre papers, which are of major importance in filtration. The other has evolved by exploiting the characteristics of the synthetic fibres formed by the extrusion of molten polymers; adaptation of this extrusion process enables these fibres to be formed directly into the paper-like sheets of the spunbonded media discussed below, which have taken a share of the markets formerly supplied by wet-laid media.

Filter sheets

Filter sheets are made in the same way as paper, i.e. by wet laying, but they are both thicker than paper and rougher in texture. They have traditionally been used in forms of filter presses and employed to clarify beverages such as beer and whisky or to sterilize pharmaceutical solutions. An array of filter sheets is shown in Figure 2.2. These sheets closely resemble thick filter paper and, in fact, were originally made from a mixture of cellulose and asbestos fibres; recent years have seen asbestos displaced, because of its health hazards, by kieselguhr. Because of the importance of the polishing duties performed by the sheet filter, the cellulose-based sheet is now being replaced by membrane filters.

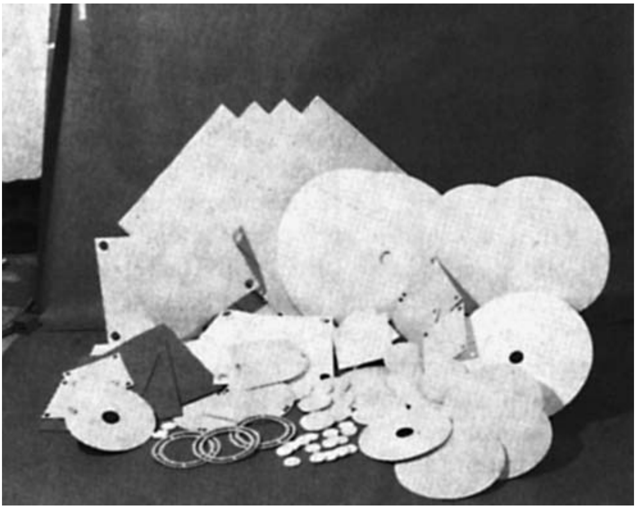


Figure 2.2 Types of filter sheet

Woven fabrics

Fabrics make up the largest component of filter media materials. They are made from fibres or filaments of natural or synthetic materials, and are characterized by being relatively soft or floppy, lacking the rigidity of dry paper, such that they would normally need some kind of support before they can be used as a filter medium.

The fibres or filaments can be made up into a fabric as they are, by means of some kind of dry-laying process, to produce a felt or similar material. Such 'non-interlaced' fabrics are generally referred to as 'nonwoven', and they are covered later in this section.

If the fibres or filaments are first spun into a continuous yarn, then the resultant yarn can be woven or knitted into a fabric, and such 'interlaced' materials are the woven fabrics covered here. If the material used in the weaving process is a single filament of wire or plastic, then the resultant material may be counted as a fabric, but is more often called a mesh, and is also covered separately later.

Textile fibres come from many sources, both natural and synthetic. The natural materials come either from vegetable sources: cotton, flax (linen), jute, and wood cellulose, or from animals: silk, wool, fur, hair. The synthetic materials are produced either from natural resources such as glass, ceramics, carbon, metals or reconstituted cellulose, or they are totally synthetic, being extruded from thermoplastic polymers.

The naturally fibrous materials all have fibres that are extremely long by comparison with their diameters, except in the case of wood cellulose, where the manufacturing process produces fibres whose lengths are measured only in millimetres.

These wood cellulose fibres are too short to spin into a yarn, and are only usable in the wet-laying processes that produce paper and related materials.

The remainder of the natural fibres have lengths measured in centimetres, and can be over 30 cm long in the case of wool, while silk can be produced as a single filament. The synthetic materials are actually produced as continuous filaments, which can then be cut or broken into fibres of any length.

Natural fibres have a diameter dictated by their source, and this is usually less than a millimetre. The synthetic fibres and filaments are mainly formed by some kind of extrusion process from the molten state, with a diameter to match that of the spinning nozzle through which they are extruded. Their diameters can thus exist in a wide range, from much greater than those of natural products, to considerably finer sizes.

The length and diameter of a natural fibre may be increased by converting the material into a yarn, although yarns may also be made up of filaments. Because of their much greater length, filaments may just be bundled together to make a yarn, although the bundles are usually twisted to give a reasonably constant diameter. The shorter, staple, fibres have to be twisted quite tightly, after being spun to line them up, in order to give adequate strength to the resultant yarn.

Yarns made from filaments are usually thin, smooth and of a lustrous appearance. Staple yarns are usually thicker, more fibrous (hairy) in appearance, and with little or no lustre.

Yarns can also be made up from tapes of various kinds. In the case of filter media, these tapes would probably be fibrillated, or made of other perforated material.

Woven fabrics are then made up from single filaments, or multifilament yarns, or from twisted staple yarn. The last of these is normally used as a single strand, but two or more spun strands may be combined into ply yarns, where the strands are twisted together, usually (but not necessarily) in the opposite sense from the twist in each strand.

Fabrics can be considered as a direct, and physically stronger, alternative to papers and are employed in a similar manner for pleated elements, etc. Fabric elements were originally the most commonly used type of filter medium for fine filtration and are generally comparable with modern paper media as regards to the performance achievable. Until the appearance of treated paper elements, they were regarded as a superior type, although the two are now strictly competitive for similar duties. Some typical filtration performance curves for these materials are shown in Figure 2.3. Treated papers are now the more common because of lower cost, but fabric elements are capable of withstanding higher working pressures with similar geometry. However, fabric elements have a lower specific resistance than paper elements and, being thicker, can also carry a heavier load of contaminant per unit area. This latter advantage is normally offset by the fact that, for the same overall size, the surface area of the fabric element is reduced because of its greater thickness.

For a similar design of element, fabric would probably be preferred for larger sizes of filter, or where a degree of true absorption is required as well as mechanical

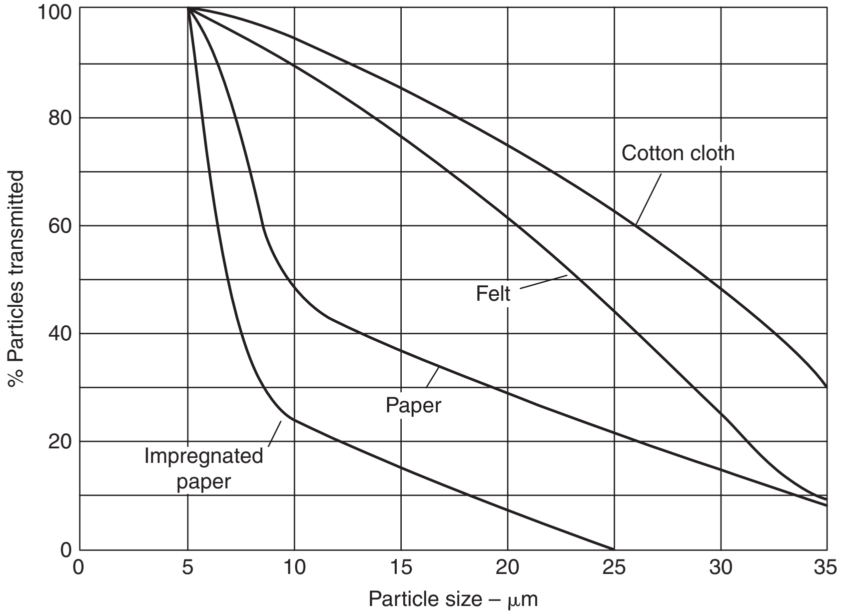


Figure 2.3 Filtration performance comparison

screening. The description 'fabric' is rather loose, compared with the term 'paper,' which is quite specific. Fabrics can comprise a whole range of materials (as in Table 2.4), woven and nonwoven, whose properties may be further modified by impregnation with synthetic resin or similar treatment. Equally the term 'cloth' is often used to describe fabric media, natural or synthetic, and even a woven wire cloth.

Woven yarn fabrics

Fabrics can be woven from yarns of many sorts. It is usually the case that *warp* yarns (those running lengthways on the loom) are the stronger, while the *weft* yarns (those running across the loom) may be bulkier and less tightly twisted – weft yarns are often called filler yarns. It is quite common for the warp to be a single, relatively stout, filament, while the weft is a yarn of some very different material. Equally, it is quite normal for both warp and weft to be made of the same filament or yarn.

The properties of a fabric, especially as regards its behaviour as a filter medium, depend very much on the way in which the yarns are woven together. Many properties, however, are intrinsic in the nature of the basic fibre or filament, and of the way in which it is made up into a yarn. There are three basic types of yarn in wide use for filter media: *monofilament,* which is a single continuous filament of synthetic material (or silk); *multifilament*, which comprises a bundle of identical continuous filaments that may or may not be twisted together; and *staple*, which is made from spun and twisted short fibres, either natural materials such as cotton and wool, or synthetic ones, which have been cut from extruded filaments. There is a fourth, but much less common, type of yarn, made from fibrillated, or split-film, tape.

The key feature of yarn type that affects filtration performance is that, with monofilament fabrics, filtration occurs in the spaces between the filaments, while, with multifilament and staple yarns, filtration can also occur within the yarns as well as between them – so the tightness of the twist in the yarn becomes important.

The physical and chemical properties of a yarn are largely those of the fibres or filaments making up the yarn. In addition to the natural fibres (mainly cotton, but with some wool and silk), and a small, but growing, number of inorganic fibres, the bulk of filter fabrics is based upon an increasingly wide range of synthetic polymer fibres. The physical and chemical properties can then be tailored to the filtration application by choosing the appropriate polymer for the fibre.

The basic material of a woven fabric (filament or fibre) and the way that this material is formed into a yarn are major parameters in the choice of a fabric as a filter medium. The variety of available woven fabrics is virtually unlimited even if only the materials from which the filaments or yarns are made, and the complexity of the yarn, are considered. To these must then be added the structure of the woven fabric itself: the way in which the yarns are woven together, and the finishing process (if any) applied to the fabric after weaving.

Woven fabrics are made up from yarns that are interlaced in a particular and regular order called a *weave*. The component yarns, warp and weft, need not be parallel to each other nor cross at right angles, but this is the case in most fabrics, and certainly it is so in filter media. The key features of a woven fabric come from the geometrical regularity of its components, and because these components are held in place, not by any rigid bonding, but by friction at their points of contact.

The binding system, or weave, is the basic factor that determines the character of the woven fabric. There are three main types of weave (plain, twill and satin) that are used in industrial textiles, although there are many other more complex systems. The differences among the weaves depend upon the pattern formed as the weft yarns are woven over or under the longitudinal warp yarns.

In *plain* weave, the weft yarn passes over and then under each succeeding warp yarn across the loom. The return weft then passes the opposite way, under then over succeeding warps, such that each weft is held securely in place by the interlocking of the warp yarns. Plain weaves can give the tightest fabric, with the highest filtration efficiency, as well as the most rigid.

Twill weaves are characterized by a strong diagonal pattern. They are formed by the passage of the weft yarn over two or more warps at a time, and then under one or more, in a regular pattern across the loom. The next weft thread follows the same pattern of over-and-under, but displaced by one warp yarn. The essential feature of a twill weave is its regularity, leading to its diagonal pattern. In a twill weave, more weft threads can be crammed in to the fabric per unit length, which gives the fabric more bulk. Compared to a plain weave with the same yarns, twill fabrics are more flexible, and therefore easier to fit into a filter.

Table 2.4 Comparative properties of filter media fabrics

	Wool	Cotton	Polyester	Acrylic	Nylon	Aramid	Polypropylene	PVC	PTFE	Glass fibre
Yarn type*	S	S	S,F,MF	S,F	S,F,MF	S,F	S,F,MF	S,F,MF	S,F,MF	S,F
Specific gravity	1.30	1.52	1.38	1.15–1.17	1.04–1.14	1.38	0.91	1.35	2.1	2.1
Tensile strength (relative, Wool = 1)	1	2–4	3.75–6.25	1.85–3.75	3.75–6.5	5–20	3.75–6	2.2	1.3	8–15
Elongation at break %	30–40	5–7	11–14	17–42	18–20	18–20	35	35–40	15	2–4
Maximum continuous service temp °C	80–90	90–100	130–135	130–135	100–110	200–220	80–90	80–90	240–260	280–300
Maximum service temp °C	100	110	140	140	120	260	90–100	90–100	280	320
Chemical resistance†										
Strong acids	F	X	G	G	X	F	E	E	E	G
Weak acids	G	F	E	E	F	G	E	E	E	G
Strong alkalis	X	G	X	G	G	G	G	E	E	E
Weak alkalis	F	E	F	G	E	G	E	E	E	G
Solvents	G	G	G	G	E	G	X	F	E	E
Oxidizing agents	X	F	E	G	F	G	X	E	E	E

Resistance to moist heat†	F	G	X	E	F	F	F	G	E	G
Specific solvents for fibre			$C_6H_5NO_2$ C_6H_5OH	CHON $(CH_3)_2$	CH_3COOH HCOOH C_6H_5OH			CH_3COCH_3 $CHCl_3$ CS_2		HF
Trade names			Dacron Terylene Terital Diolen Tergal Trevira	Orlon Dralon Redon Crylor Zerran Leacril	Nylon Perlon Rilsan Nailon Lilion	Nomex Kevlar	Courlene Merkalon Hostalen Pylen	Saran Harlan Rovyl Leavil	Teflon Fluon	Fibre-glass Vetrotex

Key
[*]S = Staple element
M = Monofilament
MF = Multifilament
†E = Excellent
G = Good
F = Fair
X = Dissolved

Satin weave extends further the concept of the twill weave, by having wider spacings between points of interlacing. Satin weave does *not* have the regular shift of weave pattern that twill has, and the result is an irregular appearance, smooth faced, with relatively long floating warp yarns. Most satin fabrics are made from smooth, lightly twisted yarns, thereby enhancing the visual effects. Fabrics with a satin weave are still more flexible than the other two types of weave, because of the increased ease of yarn-to-yarn movement: this reduces the likelihood of particles becoming trapped in the structure. The longer floats allow insertion of proportionally more warp threads, thereby further improving the surface smoothness, resulting in easier cake discharge. However, unless the threads in both warp and weft directions are packed tightly together, satin weaves do not generally achieve high filtration efficiencies, while the long floats are more susceptible to abrasive wear.

In addition to cleaning, fabrics of all kinds will usually undergo some kind of *finishing process* after weaving, in order to ensure stability of the fabric, to modify the surface characteristics, and to regulate the permeability of the fabric. Calendering and singeing are two familiar surface treatment processes, which also modify the permeability.

Synthetic monofilament fabrics

Monofilament fabrics are woven from extruded synthetic filaments produced in diameters from 30 µm to 2–3 mm.These fabrics have become important as filter media in a broad range of industries and applications. Because of their corrosion resistance, ability to withstand vibration fatigue, uniformity and economy to use, they have replaced a number of other types of media. The chemical and food processing industries, industrial hydraulics, medical, automotive and appliance markets are major users of monofilament fabrics. These fabrics are available in a range of polymer filaments including nylon, polyester, polypropylene and fluorocarbon materials, in aperture ratings from 5–5000 µm.

Synthetic monofilament fabrics, because of their ductility and memory, may be flexed repeatedly without work hardening and fatigue. They may be folded or dented with less chance of damage compared with a metal cloth, and they are lighter in weight. Some applications require the filter medium to have the physical properties of the synthetic monofilament, but with a metallized surface for static electricity dissipation. Accordingly, a metallized polyester monofilament fabric is produced coated with a 2 µm thickness of nickel.

Combined mono and multifilament fabrics are now available with useful additional characteristics. Thus such a material is used on disc filter segments, which is elastic and so will expand during the blow-back stage to help with cake release. New belt press filters and large automatic filter presses have put tremendous demands on the physical properties of the filter fabrics, which are being met by heavy dense monofilament fabrics.

The two layer, core-sheath monofilament is an interesting development, which can combine a strong core with good dirt-repellent properties. Thus the core could be made from strong polyester, coated with a sheath of fluoropolymers.

Nonwoven materials

From earliest times, woven fabrics formed the bulk of filter media. Beginning in the 1940s, with the production of a suitably bonded felt, nonwoven materials started to be used for filtration, and now they dominate the business. One reason for this is the continuing demand for finer filtration, of both liquids and gases, which can be met by very finely spun fibres, assembled into ever more complex forms of nonwoven materials.

Woollen felt is probably the oldest form of textile, and for many years was the only practical nonwoven fabric, produced by the combined action of moisture and heat on carded wool fibres. The development first of a strong adhesive-bonded felt, and then of the multiplicity of forms of dry-laid synthetic fibres, has transformed the spectrum of nonwoven media, both in format and basic material.

A nonwoven fabric, then, is one that is made up from an agglomeration of fibres, and sometimes of continuous filaments, which are held together by some form of bonding, to create a more or less flexible sheet of fabric. This will be as wide as the bed upon which the nonwoven material is laid down, and as long as the receiving rolls can accept. The chemical properties of a nonwoven fabric are dictated almost entirely by the nature of the basic fibre – unless there is a binding adhesive of significantly different properties (such as melting or softening temperature).

There are two broad classifications of nonwoven materials, into which almost all types will fall. These two classes are, to a large extent, divided by the means utilized to hold the loose fibres together:

- felts, which use the basic characteristics of the fibre to provide mechanical integrity, or which use mechanical processing (especially needling) to create a fabric
- bonded fabrics, which use some additional adhesive material to hold the fibres together, or, more commonly, rely upon the thermoplastic nature of the polymer to provide adhesion when properly heated.

This second group is then further divided in two, according to whether the formation of the basic fibre is an integral part of the manufacture of the medium (the dry-laid spun media), or not (resin and thermal bonding).

The basic felt has no added binders: some fibres, wool especially, have the ability to cling together to form a coherent mass, because of protrusions from the fibre surface. Most others can be made to adhere by suitable processing. The first step in any felt making, or dry-laying, process is the carding of the fibres, whereby they are drawn out into a thin web, which has its fibre content roughly aligned in one direction. Pieces of such web can then be placed one above the other to provide a felt of the required thickness. The successive layers can be aligned with the fibres all lying in the same direction, or in different directions to give equal directional strengths. When sufficient thickness has been achieved, the felt is compressed and heated, often after dampening, to produce its final structure. It is a fundamentally weak structure, in terms of tensile strength, and many felts are strengthened by the inclusion within their thickness of a layer of woven material, called a scrim.

The fibres in a felt are not securely locked into the mass of the fabric, and a simple felt used as a filter medium would be liable to significant loss of the fibres into the clean filtrate. Hence the need for bonding techniques to hold the fibres, such as various adhesive techniques, including the use of adhesive dispersions within the felt, the integral bonding of thermoplastic fibres, and several mechanical bonding processes, based on needling or stitch knitting, with or without the use of binding threads.

Modern felts are produced from synthetic fibres or mixtures of synthetic and natural fibres, bonded with adhesive or held together mechanically, with close control of manufacture to yield consistent density, pore size and mesh geometry, so that the cut-off performance is reasonably predictable. The structure of felts is considerably more open than papers so that whilst filtering in greater depth, specific resistance is lower and high rates of flow can be achieved with smaller element areas and low pressure drop.

High temperature resistant meta-aramid fibre has helped hot gas filtration technology to move a step closer to the industry's goal of zero emissions by providing a combination of high separation efficiency and low differential pressure.

Wool resin media

It is a common feature of solid/gas filtration, and, to a lesser extent, solid/liquid filtration, that the particles in suspension may carry an electrostatic charge, and therefore that a filter medium carrying the opposite charge will be more effective in their removal. Many different media can be given a charge for this purpose, but one in particular has had a long history of effectiveness in this way.

The filtration efficiency of wool felts against sub-micrometre aerosols can be greatly increased by the addition of a special resin, which produces a very long-lived electrostatic effect. The electrostatic charge is generated during processing, the resin powder being agitated in the wool matrix, enabling charge transfer to occur. The wool then has a positive charge and the resin a negative charge, the filter being overall electrically neutral. The random distribution of the resin powder on the wool fibres, and random array of the wool fibres in the filter, means that the electrical field is not uniform and is therefore very effective at capturing both charged and uncharged particles (non-uniformity induces a dipole on to neutral particles, thereby facilitating electrical capture).

The electrical charge thus imparted gives wool resin a high efficiency for filtration of sub-micrometre particles of better than 99.5%, whilst having a very low resistance to air flow. The very high electrical resistivity of the resin means that once generated the charge and filter efficiency are maintained for many years, although tropical conditions can reduce its life.

Wool resin was first developed for use in respirators for combat use in World War I, and today it is still used extensively in the respirator industry, 90 years after its development. Its combination of low breathing resistance and high filtration efficiency is very competitive against more recent materials. Vacuum cleaners and other freestanding dust collectors take advantage of the high efficiency of wool resin against asbestos and other harmful dust. Wool resin is also employed in heating and ventilation work, for example in making clean rooms for computer suites, and prefilters for HEPA filters.

Needlefelts

For some, undemanding, applications, a simple felt can provide suitable filtration performance, without any form of strengthening. However, their low tensile strengths, and the ease with which fibres can become detached, make simple felts unattractive for most filtration purposes, and some mechanical (or chemical) strengthening is required.

Needle punching is the most common mechanical strengthening technique, which originated in the 1880s with natural fibres, but it is only since about the early 1970s that it has come into prominence because of its suitability to the processing of many synthetic fibre felts. A thick 'batt' of several layers of carded fibre is assembled, and then compressed into a denser structure by punching with an array of special barbed needles reciprocating at speeds up to 2000 strokes/minute, and moving perpendicularly to the felt layer. With perhaps 100 or more needle penetrations per cm^2, the effect is to entangle the fibres in the thickness of the felt, and to reduce the thickness substantially, to a degree that is controlled as desired. Punching can be from one side of the felt, or from both sides simultaneously, which improves the uniformity of the felt.

Needlefelts are used extensively as bag filters for the filtration of dusts and gases, because of their above-average collection efficiency. Common applications include the cement industry, steel and aluminium plants, spray drying, coal grinding, sand blasting, the food industry, detergent manufacturing, ship unloading, pneumatic conveying and hot gas filtration processes where metal fibre felts and ceramic fibres are used. Some typical applications for filter fabrics of various kinds are shown in Table 2.5 with their key characteristics.

Most felts are mechanically strengthened by needling, but an alternative, and more specialized, technique employs a set of high pressure water jets to fix the fibres in place – a technique known as hydroentanglement. Hydroentangled felts are also said to be spunlaced.

Meltspun materials

Just as needlefelts took market shares from some woven fabrics as filter media, so now are the newer meltspun synthetics expanding quickly into most filtration applications. These are the class of media that start with a filament of molten thermopolymer being extruded from a fine nozzle. As it leaves the nozzle the filament is quenched rapidly in an air stream, and then laid down on a belt moving along below the extrusion nozzle.

If a row of nozzles, or spinarets, is mounted across the width of the collecting belt, and is caused to oscillate in the direction of the nozzle row, then the filaments fall onto the belt in a random fashion, to form a continuous strip of material. This is then pressed at a temperature sufficient to melt the collected filaments at their points of contact to form a strong coherent material, a process called spun bonding. If an air stream just below the exits from the spinarets is directed across the path of the falling filament, it will break the filaments into relatively short pieces, and the resultant fibres can then be collected on a moving belt, and pressed and sintered,

Table 2.5 Typical applications for filter fabrics

Material	Suitable for:	Maximum service temp °C	Principal advantage(s)	Principal disadvantage(s)
Cotton	Aqueous solutions, oils, fats, waxes, cold acids and volatile organic acids.	90	Inexpensive.	Subject to attack by mildew and fungi.
Jute wool	Aqueous solutions.	85	Easy to seal joints in filter presses.	High shrinkage, subject to moth attack in store.
	Aqueous solution and dilute acids.	80		
Nylon	Acids, petrochemicals, organic solvents, alkaline suspensions.	150	High strength or flexibility.	Absorbs water; not suitable for alkalis.
			Easy cake discharge. Long life.	
Polyester (Terylene)	Acids, common organic solvents, oxidizing agents.	100	Good strength and flexibility. Initial shrinkage.	Not suitable for alkalis.
PVC	Acids and alkalis.	up to 90		May become brittle. Heat resistance poor.
PTFE	Virtually all chemicals.	200	Extreme chemical resistance. Excellent cake discharge.	High cost.
Polyethylene	Acids and alkalis.	70	Easy cake discharge.	Soften at moderate temperatures.
Polypropylene	Acids, alkalis, solvents (except aromatics and chlorinated hydrocarbons).	130	Low moisture absorption.	
Dynel	Acids, alkalis, solvents, petrochemicals.	110		
Orlon	Acids (including chromic acid), petrochemicals.	Over 150		
Vinyon	Acids, alkalis, solvents, petroleum products.	110		
Glassfibre	Concentrated hot acids, chemical solutions.	250	Suitable for a wide range of chemical solutions, hot or cold (except alkalis).	Lacks fatigue strength for flexing. Abrasive resistance poor.

and this process is called melt blowing. It is this integral production of filament or fibre followed immediately by its laying down as the medium that distinguishes the *spun* media from the felts – which are made, usually, from bundles of fibre bought in from a separate supplier.

Since the late 1960s, these novel manufacturing processes have developed rapidly, to give the resulting materials a commanding position in the filter media business. The development has been so rapid that a standard set of terms has not yet been agreed on an industry wide basis – some refer to all such materials as spunbonded, others differentiate between spunbonded and meltblown, while terms such as melt spun and flash spun are also used, while the latest very fine fibre materials are also called spun webs. The earliest such processes were those first called melt spinning, now generally known as spun bonding, and which remain important to the present day. They produce relatively coarse filaments, while the newer developments, such as melt blowing, have enabled the production of much finer fibres. Spunbonded media are the stronger, and are often found as a sandwich structure, with a layer of spunbond in each side of an inner layer of meltblown material.

The meltspun materials are usually formed into thin sheets, like paper or cardboard, and are then widely used in pleated form, as cartridges, shown typically in Figure 2.4. These media are capable of exceedingly fine degrees of filtration, and a great deal of microfiltration is now undertaken with them.

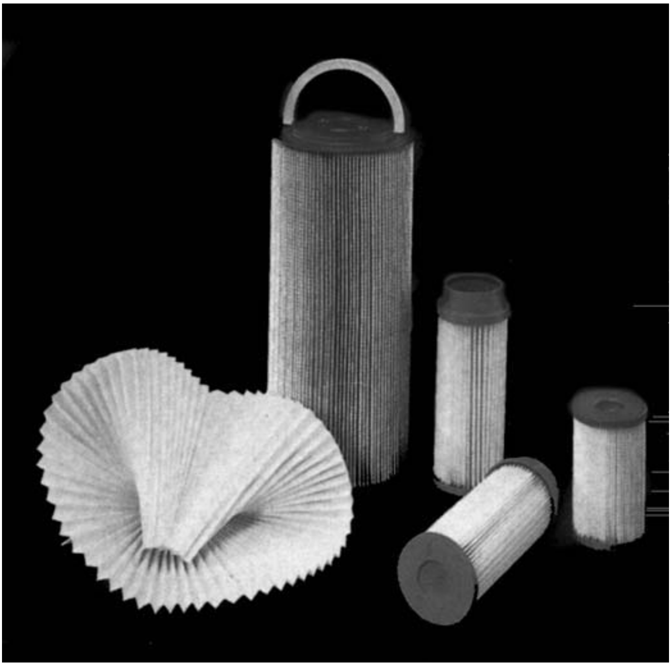


Figure 2.4 Pleated meltspun materials

The differences between the two main classes of dry-laid spun material are significant in terms of filtration behaviour, but both are available with the same range of finishing processes as are used for woven and needlefelt materials: calendering, singeing and coating. The lamination of different materials is also an important feature of dry-laid spun media.

The latest technique, of major interest because of its ability to produce very fine (nano) fibres, is electrospinning. This uses an electric field below the spinneret to draw out the filament before it is laid down as the finished material, with final filament or fibre diameters controlled by the electric field.

Bonded porous media

There is an important group of media materials that are not fabrics in the normally accepted sense of the word, because they are mostly not flexible, but they are made in similar ways, and serve a similar purpose, so they are included here. These are the sheets and tubes made from bonded components: fibres and granules of natural and synthetic materials. They are mainly only coarsely porous, because it is much more difficult to form very finely granular solids into useful shapes, but some fibre based materials are capable of very fine cut-off points. An important feature of this group of media is the proportion of inorganic materials that it contains, although polymeric materials are also highly featured.

These media are made by the aggregation of small particles (granules or fibres) of the basic material into useful shapes, either between rolls or in a mould. The aggregate is dosed with a bonding resin and then heated to a temperature where the resin melts and holds the mass of granules or fibres in the required shape. Alternatively, the aggregate is heated to a temperature close to the melting point of the material, under pressure, so that there is localized melting at the points of contact among the particles (and any binder used in the aggregation is driven off or incinerated).

This bonding or sintering process confers an element of rigidity upon the resulting materials, so that they are used, for filtration purposes, either as sheets (including sheets cut into appropriately shaped pieces), or as tubes (open ended or closed at one end), shown in Figure 2.5. Some of the materials, especially the plastic ones, and in relatively thin sheets, are flexible enough to be rolled up, as can be seen in Figure 2.6. This is a very useful group of media, with the inorganic nature of some of the materials enabling their use at quite high temperatures.

These media are made from granules of plastic and metals, and from fibres of plastic, metals, glass and carbon. They are also made by the laying down of meltspun polymeric fibres or filaments onto a rotating perforated core, so as to create a cylindrical filter cartridge.

Inorganic materials

As already mentioned, a major feature of the inorganic materials included here is their ability to operate at high temperatures. The importance of this particular set of applications is continually growing.

Figure 2.5 Porous plastic tubes

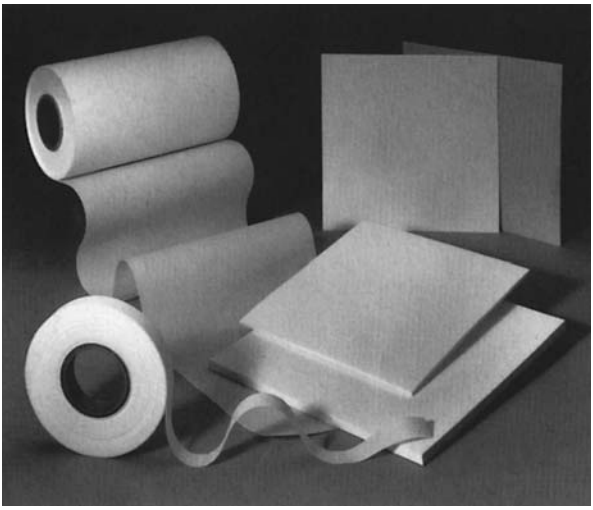


Figure 2.6 Porous plastic sheet media

Classed under this heading are media made from metal powder and fibres, ceramic powder and mineral wools, glass powder and carbon fibres (used for their mechanical separation ability, not as adsorbent).

Metal media are mostly supplied in sintered form, since any materials that escape from the medium would be quite harmful downstream. Sintered metal fibres have a very high porosity, a low resistance to flow and a high dirt-holding capacity. The fibres are long with controlled diameters ranging from 1–30 µm. Some typical metal fibre elements are shown in Figure 2.7. Sintered metal media are used extensively for polymer applications, especially central polymer filter and spinback applications, where they provide for increased on-stream life. Other applications using high grade alloys include the chemical and process industries as well as applications in nuclear containment venting and nuclear waste streams. The mechanical strength of sintered metal media is around double that of typical powder based media or ceramics or glass fibres. Non-graded sintered metal fibre is commonly used in corrugated or pleated form for the filtration of low viscosity fluids such as hydraulic oils and fuels.

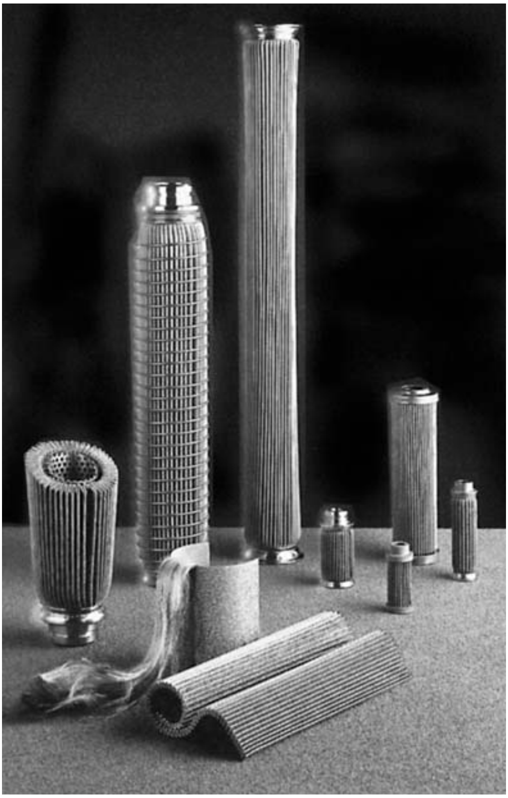


Figure 2.7 Metal fibre cartridge media

Ceramic filter elements have a particular application for higher fluid temperatures and for handling corrosive fluids. Elements made from vitreous bonded refractory ceramic aggregate also have a high resistance to physical and thermal shock. Ceramic elements can be cast or moulded in various element forms with varying degrees of porosity and uniformity of structure. Void volumes are typically up to 50%.

Microporous types can be produced with pore sizes down to 1 µm. Ceramic elements can be used for filtering both air and liquids. They are particularly suitable for use with acids and alkalis. Properties of media for use with higher temperature fluids are shown in Table 2.6.

Table 2.6 Properties of high temperature media

	Structure		
Properties	Granular	Woven	Fibrous
Porosity	40–60%	35–55%	80–90%
Permeability	low	corresponding to weaving technique and media thickness	high
Weight	high	low	lower than granular structure
Pressure drop	50–100 mbar	20–35 mbar	<30 mbar
Collection efficiency	high	medium, especially with flexible filter media	high

Mineral wools can also be regarded as a ceramic material. They are rather like natural felts, with random fibre distribution in three dimensions, offering a tortuous path for filtration in depth. Their densities are low, permeability is high and with suitable packing very fine filtration can be achieved with minimum pressure drop. It is often necessary, however, that flow velocities be kept very low in order to avoid bunching of the fibres, with a consequent drop in efficiency. This somewhat limits their application with liquid filtration, although they are widely used for pure air filtration and the removal of solid particles from gases. In the latter respect mineral fibres may be used at working temperatures well above those possible with other non-metallic filters, for example at temperatures of 500°C or even higher for short periods.

Performance down to sub-micrometre size is possible with mineral wool filter pads. In the case of ultra-fine gas or air filtration, a nominal optimum velocity for flow rate is 10 m/min decreasing to 5 m/min at a working temperature of 150°C. Flow velocities in excess of 15 m/min will normally promote bunching, but velocities as high as 40 m/min per minute may be accommodated where some loss of filtration efficiency can be tolerated. Typically, a very fine fibre filter pad of 12.5 mm thickness should be capable of removing solid particles from gases down to 0.1 µm at gas velocities of the order of 10 m/min through the pad, with only nominal resistance. Increasing the filter pad thickness above an optimum does not necessarily increase filtration efficiency, although it increases the possibility of trapping still finer particles. Thus, for sterile air and similar applications, the filter pad thickness may be as great as 100 to 125 mm.When used for ultra-fine and sub-micrometre filtration in this way, it is also desirable that the air be prefiltered to remove coarser particles, leaving the pad itself to deal with the finer contaminants. This will increase the life of the filter pad, which may then be as high as three to six months under continuous use.

Glass fibres in blanket or pad form are widely used as a primary stage air filter. By modification of the conventional spinning process, the blanket as manufactured can have progressively increasing density from one side to the other, e.g. sparsely packed large diameter fibres on the dirty air side, gradually giving way to more densely packed small diameter fibres towards the inner surface. This effect is produced by an ageing process, which conditions the blanket, followed by a further operation to expand the fibres. Expansion produces an aerated filter medium of greatly increased volume and thus high porosity. Binders added prior to this stage can act as fibre lubricants to assist expansion. The expanded blanket can then be oven-treated to cure the binder and cement the fibres together to produce a rigid, light weight mass.

Medium and fine glass filter pads are produced from a blend of glass fibre strands and glass microfibres bonded together with a binder to form thin sheets. A typical filter medium pad is then constructed by interleaving a continuous length of glass fibre medium, concertina-folded over wire mesh or perforated aluminium separators. Ultra-fine filters such as HEPA and ULPA elements use a sheet form of medium produced only with glass microfibres. The complete element may be constructed as previously described, interleaved with spacers cut from microglass paper.

Synthetic filter media such as the meltblown and spunbonded polymeric materials are beginning to be used more frequently in place of glass fibres.

Commercial carbon fibre is produced in fibre diameters of the order of 5–10 μm from a variety of starting materials such as acrylic textile fibres, cellulose-based fibres or even pitch. They offer a possible alternative to organic fibres and glass fibres for filter pads and felts for extreme chemical and temperature uses, with the additional advantage that the material can be activated and is thus able also to perform as an adsorbent filter. The main limitation of carbon fibre as a filter medium has been its expense, coupled with the fact that the current fibre diameter sizes available mean that they cannot achieve the performance of current HEPA filters using microglass fibres. However, carbon fibres down to nanometre diameters are now becoming commercially available and these are going to be an exceedingly important component of the fibre filter media business.

2D. WOVEN WIRE AND SCREENS

Media made from metals have already been mentioned, in Section 2C, in the form of sheets and tubes made from metal fibres and powders, usually sintered together to retain their structure. By far the greatest amount of filter media made from metal, however, is in the form either of woven wire or perforated sheets, which are covered in this part of Section 2, with the common features of high strength, and corrosion and abrasion resistance conveyed by the basic material of construction. The other common feature, of great importance to their use for filtration, is that these materials can be made with apertures of precise sizes, which also comes from their being made of metal.

It should be noted, however, that the edge filters described in Section 2E are also mainly made of metal and made with precise apertures. It should also be noted that every type of filter medium described in this part as made from metal can also be made of plastic materials, with almost as much strength and almost as much precision in aperture size. Corrosion resistance may actually be higher with plastic wire screens or sheets than for some metals.

There are two major applications for which these metallic media are primarily used: the separation of solid particles by size, and the coarse screening of gas or liquid flows ahead of some finer processing stage. In the coarser, macrofiltration processes these are very versatile materials: all of the dry classification (sieving, sifting) operations are covered here, as are almost all of the applications of filters for straining and coarse filtration, both of which rely upon the precise size and shape of the apertures in the mesh or sheet.

There are three broad classes of media covered under the above heading: woven wire meshes, sheets perforated with a variety of holes, and elements made up from preformed materials such as rods or bars. Some overlap obviously exists between the woven meshes of this sub-section and the woven monofilament materials of Section 2C.

Woven wire mesh

The weaving of wire is no different, in principle, from the weaving of any other yarn: warp wires are set up along the loom and weft wires across it. The product is a roll of woven mesh, which then is processed in a variety of ways, to produce the filter medium (or for many other purposes). The terms wire cloth and gauze are frequently used to refer to meshes woven from finer grades of wire, while the term bolting cloth refers to light weight versions of square mesh cloths, comprising those based on the finest wires (and originally used for the sieving of flour).

A wide variety of wire meshes is produced by weaving individual wires of either ferrous or non-ferrous metals on looms up to 2 m wide. Two main categories of mesh can be distinguished, in terms basically of the shape of the apertures. One category utilizes plain weave with single wires of the same diameter for the warp and weft, to form rectangular apertures (the great majority being square); many of these are the screens typically used for sieving and sizing operations. The other category is known as zero aperture filter cloths, with the wires pressed closely together to leave as little space as possible between them, and made in a number of more complex weaves, such as Dutch twills, which are commonly used in pressure and vacuum process filters.

In a woven wire mesh, each warp or weft wire bends where it passes over or under a wire of the other kind. This crimping of the wires occurs as part of the weaving process for fine wires, but the crimp has to be imposed on the wire above a certain thickness, before it is fed into position. Although this adds a stage to the weaving process, it has the valuable benefit of holding the crossing wires in place should the wire mesh move or vibrate.

Woven wire cloth has been widely used for filtration for well over 100 years and is available in an extremely wide range of materials and mesh sizes. It can be woven from virtually any metal ductile enough to be drawn into wire form, preferred metals being phosphor bronze, nickel-chrome stainless steels, and monel. Other materials widely used include aluminium alloys (combining good strength with light weight and good corrosion resistance), copper (cheaper than bronze but not suitable for corrosive conditions), brass (stronger than copper but more subject to corrosion) and mild steel or coated mild steel (such as galvanized or tinned). Nickel, nickel-chrome alloys and titanium may be used for high temperature duties. Special alloys such as Inconel, Hastelloy and Incoloy are also used.

The minimum practical size of wire that can be used depends on the alloy from which it is made, the strength required in the mesh, the operating temperature, and the degrees of corrosion and abrasion likely to be experienced in service. Thus, finer wire diameters in aluminium, brass, bronze or copper are not normally used for other than light duties. Stainless steel wire on the other hand is available and is used down to 15 μm.

The key dimensions of wire mesh are illustrated in Figure 2.8, for plain weave and square mesh (the usual form for plain woven wire meshes). Aperture width, w, is the distance across the aperture, between the bounding wires, measured in the projected plane at the mid positions. The wire diameter, d, is the diameter of the wire forming the mesh. The pitch, p, is the distance between the middle points of two adjacent wires and therefore is the sum of the aperture width and the wire diameter:

$$\mathrm{p} = w + d$$

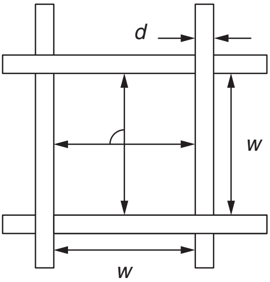


Figure 2.8 Mesh dimensions

The number of apertures per unit length, n, is the number of apertures that are counted in a row one behind the other for a given unit length (which may be 1 cm, 1 in or any other convenient unit). The term ‘Mesh’ is a traditional one referring to the number of apertures per linear inch, so that, with the aperture dimensions measured in millimetres:

$$\text{Mesh} = 25.4/\text{p}$$

and

$$n \text{ (per cm)} = 10/\text{p}$$

The open screening area, A_0, is the percentage of the total screening surface represented by all the apertures in that surface, or the ratio of the square of the aperture width to the square of the pitch:

$$A_0 = 100\text{w}^2/\text{p}^2$$

Mesh numbers may range from 2 (two apertures per inch) up to 400. Meshes are usually classified as coarse (w = 1–12 mm), medium (w = 0.1–0.95 mm) and fine (w = 0.02–0.16 mm or 20–160 µm). A typical set of wire mesh dimensions is given in Table 2.7.

Table 2.7 Typical set of wire mesh dimensions

Aperture		Wire dia	Open area	Mesh	Wire dia
µm	mm	mm	%	~	in
25	0.025	0.025	25	500	0.0010
28	0.028	0.025	28	480	0.0010
32	0.032	0.028	28	425	0.0011
38	0.038	0.025	36	400	0.0010
40	0.04	0.032	31	350	0.0012
42	0.042	0.036	29	325	0.0014
45	0.045	0.036	31	315	0.0014
50	0.05	0.036	34	300	0.0014
56	0.056	0.040	34	270	0.0016
63	0.063	0.040	37	250	0.0016
75	0.075	0.036	46	230	0.0014
75	0.075	0.053	36	200	0.0021
80	0.08	0.050	38	200	0.0020
85	0.085	0.040	46	200	0.0016
90	0.09	0.050	41	180	0.0020
95	0.095	0.045	46	180	0.0018
100	0.1	0.063	38	150	0.0025
106	0.106	0.05	46	165	0.0020
112	0.112	0.08	34	130	0.0032
125	0.125	0.09	34	120	0.0035
140	0.14	0.112	31	100	0.0045
150	0.15	0.10	36	100	0.0040
160	0.16	0.10	38	100	0.0040

(*Continued*)

Table 2.7 (Continued)

Aperture		Wire dia	Open area	Mesh	Wire dia
µm	mm	mm	%	~	in
180	0.18	0.14	32	80	0.0055
200	0.2	0.125	38	80	0.0050
200	0.2	0.14	35	75	0.0055
224	0.224	0.16	34	65	0.0065
250	0.25	0.16	37	60	0.0065
280	0.28	0.22	31	50	0.009
315	0.315	0.20	37	50	0.008
400	0.4	0.22	42	40	0.009
400	0.4	0.25	38	40	0.010
425	0.425	0.28	36	36	0.011
500	0.5	0.20	51	36	0.008
500	0.5	0.25	44	34	0.010
500	0.5	0.32	37	30	0.012
560	0.56	0.28	44	30	0.011
560	0.56	0.36	37	28	0.014
630	0.63	0.25	51	30	0.010
630	0.63	0.28	48	28	0.011
630	0.63	0.40	37	25	0.016
710	0.71	0.32	48	25	0.012
710	0.71	0.45	37	22	0.018
800	0.8	0.32	51	22	0.012
800	0.8	0.5	38	20	0.020
–	1	0.36	54	18	0.014
–	1	0.63	38	16	0.025
–	1.25	0.4	57	16	0.016
–	1.6	0.5	58	12	0.020
–	2	0.56	61	10	0.022
–	2.5	0.71	61	8	0.028
–	3.15	0.8	64	6	0.032
–	4	1	64	5	0.04
–	5	1.25	64	4	0.05
–	6.3	1.25	70	3½	0.05
–	7.1	1.4	70	3	0.055
–	8	2	64	2½	0.08
–	10	2.5	64	2	0.10
–	12.5	2.8	67	–	0.11
–	16	3.2	69	–	0.12

Sets of test sieves are available, matching the various standard ranges of mesh size. These are supplied in standard-sized holders, which fit one into the other, and which can be held in the frame of a shaker machine. The design of the mesh holder is important, since it is essential that the mesh be held fast and taut. There should be a bevelled entry to the mesh area to ensure that all of the material to be sieved is transferred to the mesh area when hand-sieving at an angle of 30°. Table 2.8 shows the comparative mesh sizes for some international and trade standard series of meshes.

Types of weave

The weave of any mesh is usually one of six basic types, but there are also some minor variations. Square mesh (Figure 2.9) has each weft wire passing alternately over and under each warp wire. The opening can be square or rectangular (much less commonly) and so this weave is more correctly referred to as plain or double-crimped weave. It is generally satisfactory in strength, from 10 to 60 Mesh, but finer meshes demand the use of such smaller diameter wires that there is an appreciable loss of strength. The width of the opening, it will be appreciated, is limited by the diameter of the wire and thus finer meshes can only be woven from finer wires.

Twilled weave is the next strongest, with each weft wire progressing one wire at a time, alternately crossing over two and then under two warp wires, producing a marked diagonal pattern (Figure 2.10). This allows the use of larger wire diameters for a given mesh and thus greater strength, but with proportionately smaller openings. This can be offset to some extent, if necessary, by reducing the number of weft wires, resulting in rectangular apertures.

For filtration purposes, the most widely used forms of woven wire are the Dutch or hollander weaves, wherein the warp and weft are of different diameter, generally with a corresponding difference in the relative numbers of warp and weft wires. If the warp wires are thicker, the result is the ‘plain Dutch weave’; the alternative is for the weft wires to be the thicker, giving the ‘reverse plain Dutch weave’.

Plain Dutch weave is the first of the zero aperture weaves (i.e. no openings can be seen at right angles to the mesh surface). It is actually a plain weave, with the larger diameter wires as the warp and straight, while the weft wires are crimped at each pass (Figure 2.11 – which actually shows warp and weft as the same diameter). The range of cloths produced in this weave extend from 340 μm down to about 15 μm in aperture size (i.e. coarse to medium). The openings are small in size, triangular in shape and not straight through the mesh. The cloth itself is firm and compact with good strength. Two variations of this type of weave exist, the first of which uses two warp wires instead of one and which is normally chosen for openings below 14 μm or when additional strength above 14 μm is required. The second uses much finer warp and weft wires, in flat groups of three or four, leading to better flow rates and higher contaminant tolerance.

Reverse plain Dutch weave is similar except that the thicker wire is in the weft (Figure 2.12). Reverse plain Dutch weave is substantially stronger, and is in fact the strongest filter weave in commercial production; as a result, coupled with its good flow characteristics and high dirt-holding capacity, it is widely used industrially.

By a similar combination of warp and weft wires of different diameters, two basic forms of twilled Dutch weave are produced. The use of heavy warp wires

Table 2.8 Test sieves – international comparisons

Woven wire cloth for test sieves							Width of apertures						
1	2	3	4	5	6	8	10	11	12	13	14	15	16
ISO 565 Table 1 R 20	DIN 4188	AFNOR NF X 11-501	CANADA 8-GP-2M	UdSSR GOST 3584	ITALY UNI 2331 Parte 2[a]	JAPAN Z 8801	BS 410 Table 2	Appx. C	NETHER-LANDS NEN 2560	ASTM E 11		TYLER® Standard Screen Scale Sieve Series	ISO 565 Table 2 R 40/3
1983	1977	1970	1976	1973	1980	1982	1976		1980	1981		1910	1983
☐	☐	☐	☐	☐	☐	☐	☐		☐	☐		☐	☐
µm	mm	µm	µm	mm	mm	µm	Mesh	µm	µm	µm	No	Mesh	µm
20	0.2	20	20	–	–	–	–	–	–	–	–	–	20
22	0.022	22	22	–	–	22	–	–	–	–	–	–	–
25	0.025	25	25	–	–	–	–	–	–	–	–	–	25
–	–	–	–	–	–	26	–	–	–	–	–	–	–
28	0.028	28	28	–	–	–	–	–	–	–	–	–	–
32	0.032	32	32	–	–	32	–	–	–	–	–	–	32
36	0.036	36	36	–	–	–	–	–	–	–	–	–	–
–	–	–	–	–	–	38	38	400	38	38	400	400	38
40	0.04	40	40	0.04	0.04	–	–	–	–	–	–	–	–
45	0.045	45	45	0.045	0.045	45	45	350	45	45	325	325	45
50	0.05	50	50	0.05	0.05	–	–	–	–	–	–	–	–
–	–	–	–	–	–	53	53	300	53	53	270	270	53
56	0.056	56	56	0.056	0.056	–	–	–	–	–	–	–	
63	0.063	63	63	0.063	0.063	63	63	240	63	63	230	250	63
71	0.071	71	71	0.071	0.071	–	–	–	–	–	–	–	–
–	–	–	–	–	–	75	75	200	75	75	200	200	75

80	0.08	80	80	0.08	0.08	–	–	–	–	–	–	–	–
90	0.09	90	90	0.09	0.09	90	90	170	90	90	170	170	90
100	0.1	100	100	0.1	0.1	100	–	–	–	–	–	–	–
–	–	–	–	–	–	106	106	150	106	106	140	150	106
112	0.112	112	112	0.112	0.112	–	–	–	–	–	–	–	–
125	0.125	125	125	0.125	0.125	125	125	120	125	125	120	115	125
140	0.14	140	140	0.14	0.14	–	–	–	–	–	–	–	–
–	–	–	–	–	–	150	150	100	150	150	100	100	150
160	0.16	160	160	0.16	0.16	160	–	–	–	–	–	–	–
180	0.18	180	180	0.18	0.18	180	180	85	180	180	80	80	180
200	0.2	200	200	0.2	0.2	200	–	–	–	–	_	–	–
–	–	–	–	–	–	212	212	72	212	212	70	65	212
224	0.224	224	224	0.224	0.224	–	–	–	–	–	_	–	–
250	0.25	250	250	0.25	0.25	250	250	60	250	250	60	60	250
280	0.28	280	280	0.28	0.28	–	–	–	–	–	_	–	–
–	–	–	–	–	–	300	300	52	300	300	50	48	300
315	0.315	315	315	0.315	0.315	–	–	–	–	–	_	–	–
355	0.355	355	355	0.355	0.355	355	355	44	355	355	45	42	355
400	0.4	400	400	0.4	0.4	–	–	–	–	–	_	–	–
–	–	–	–	–	–	425	425	36	425	425	40	35	425
450	0.45	450	450	0.45	0.45	–	–	–	–	–	_	–	–
500	0.5	500	500	0.5	0.5	500	500	30	500	500	35	32	500
560	0.56	560	560	0.56	0.56	–	–	–	–	–	_	–	–
–	–	–	–	–	–	600	600	25	600	600	30	28	600
630	0.63	630	630	0.63	0.63	–	–	–	–	–	_	–	–
710	0.71	710	710	0.70	0.71	710	710	22	710	710	25	24	710
800	0.8	800	800	0.8	0.8	–	–	–	–	–	_	–	–
–	–	–	–	–	–	850	850	18	850	850	20	20	850
900	0.9	900	900	0.9	0.9	–	–	–	–	–	_	–	–
1000	1	1000	1000	1	1	1000	1000	16	1000	1000	18	16	1000

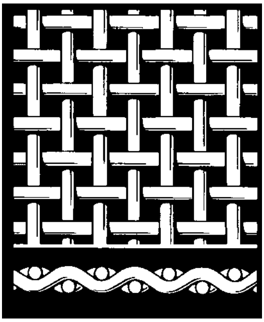


Figure 2.9 Plain weave, square mesh

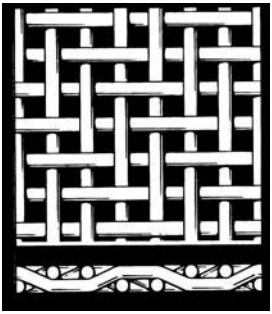


Figure 2.10 Twill weave, square mesh

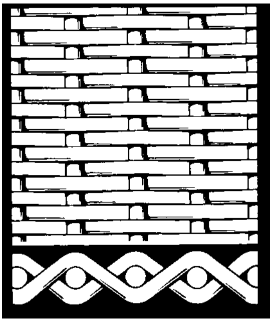


Figure 2.11 Plain Dutch weave

results in Dutch twilled weave (Figure 2.13), which permits the production of the very finest grades of woven wire cloths, while also having the advantage of a very smooth surface on both sides; its disadvantage is a relatively high resistance to flow. With heavy weft wires, twilled reverse Dutch weave is formed; this offers less resistance to flow but with a corresponding decrease in sub-micrometre retention characteristics and with rough surfaces on both sides.

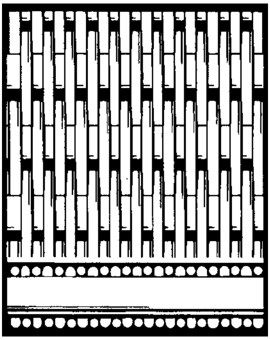


Figure 2.12 Reverse plain Dutch weave

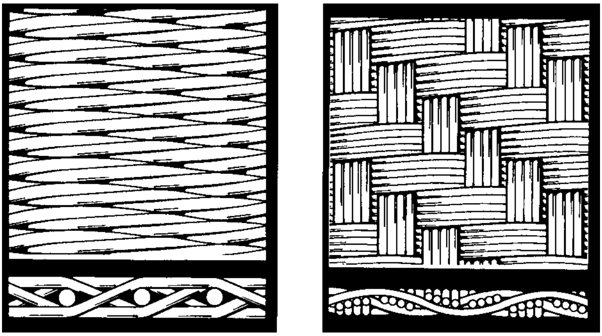


Figure 2.13 Dutch twilled weave

A summary of the main types of weave for wire cloth is given in Table 2.9, while Table 2.10 compares the performance characteristics of wire mesh media with other forms of metallic filter media.

Sintered wire mesh

The crimping of the individual wires in a mesh goes a long way towards ensuring the stability of the mesh, and therefore the constancy of the apertures of the mesh, if the mesh is subject to movement or vibration in use. Where absolute stability is required, this can be achieved by sintering the mesh, so that the wires fuse together at their contact points.

Sintering is even more important in maintaining the stability of multi-layer meshes. Composite constructions of wire mesh, consisting of several layers of mesh sintered together, are aimed at producing a high strength porous sheet of greater durability than single layer mesh. At the same time, the layer construction provides filtration in depth, with increased dirt-holding capacity.

As a general rule, different meshes are used for each layer, chosen and oriented to provide optimum strength with a minimum of masking of apertures in adjacent

Table 2.9 Principle weaves for wire cloths

Name	Characteristics	Absolute rating range µm	Remarks
Square plain or twilled	Largest open area and lowest flow resistance. Aperture size is the same in both directions.	20–300+	Most common type of weave. Made in all grades from coarse to fine.
Plain Dutch single weave	Good contaminant retention properties with low flow resistance.	20–100	Openings are triangular.
Reverse plain Dutch weave	Very strong with good contaminant retention.	15–115	
Twilled Dutch double weave	Regular and consistent aperture size.	6–100	Used for fine and ultra-fine filtering.

Table 2.10 Metal filter performance comparisons

	Metal fabrics			Sintered metal powder	Edge wire
	Square weave	Dutch weave	Fibre metal felt		
Primary type of filtration	Surface	Surface	Depth	Depth	Surface
Approximate minimum absolute micrometre rating	50	5	5	4	50
Porosity	Moderate	Moderate	High	Low	Low
Permeability	High	Low	Moderate	Low	High
On stream life	Moderate	Low	High	Low	Low
Cleanability	Excellent	Good	Good	Acceptable	Excellent

layers. Final bonding is then achieved by sintering, resulting in a porous one-piece material that is dimensionally stable with minimum possibility of delamination. The lower layers are usually of coarse mesh to provide the strength; then there will be one or two layers of fine mesh for the filtration, topped by a coarser back-up layer. Nominal ratings for such media can be as low as 5 µm.

Perforated plate

Perforated metal sheets are more rigid and can be made stronger than woven wire cloths and so they find particular applications in strainers, coarse filters and screens. Perforated metal strainers have a predictable and consistent performance because the size of the screen openings is controlled in the manufacturing process.

In their simplest form they can consist of a perforated metal sheet with an array of punched holes, the diameter of the holes providing an absolute cut-off rating, and the number of holes per unit area governing the resistance to flow. A typical standard screen of this type will have something like 15 holes/cm^2, with a diameter of 1.5 mm, whilst a fine screen may have 96 holes/cm^2 of a diameter of 0.55 mm. A typical set of hole dimensions is given in Table 2.11 for several different hole shapes, together with the open area for each pattern.

Table 2.11 Typical set of perforated plate hole dimensions

Size of hole		% Open area
mm	in	
Round holes		
0.38	0.015	10
0.55	0.0215	26
0.70	0.0275	20
0.80	0.0315	32
1.09	0.043	25
1.40	0.049	25
1.50	0.055	32
1.5	0.059	37
1.64	0.065	36
1.75	0.069	39
2.16	0.085	33
2.45	0.097	36
2.85	0.112	50
Square hole (parallel)		
1.50	0.059	44
3.17	0.125	44
6.00	0.236	34
6.35	0.250	44
7.00	0.275	41
9.52	0.375	44
11.00	0.437	49
12.70	0.500	44
19.05	0.750	56
25.40	1.00	64
Square hole (alternate)		
1.75	0.069	32
3.17	0.125	32
4.75	0.187	44
6.35	0.250	44
7.93	0.312	64
9.53	0.375	56
11.10	0.437	60
12.70	0.500	53
19.05	0.750	56
25.40	1.0	57
Diamond squares		
4.75	0.187	36
9.52	0.375	49
12.70	0.500	48
15.87	0.625	42
19.05	0.750	44
25.40	1.0	43
Round end slots (alternate)		
10.00 × 0.50	0.394 × 0.019	13
10.00 × 1.00	0.394 × 0.039	23
10.00 × 1.50	0.394 × 0.059	32
20.00 × 1.50	0.787 × 0.059	34
10.00 × 2.00	0.394 × 0.079	30
20.00 × 2.00	0.787 × 0.079	30
13.00 × 2.50	0.511 × 0.098	28
20.00 × 2.50	0.787 × 0.098	31
12.00 × 3.00	0.472 × 0.118	38
20.00 × 3.00	0.787 × 0.118	47
25.00 × 3.50	0.984 × 0.137	38
Square end slots (parallel)		
10.00 × 0.40	0.394 × 0.016	14
10.00 × 0.56	0.394 × 0.022	19
10.00 × 0.76	0.394 × 0.03	25
20.60 × 1.10	0.812 × 0.043	33
20.32 × 1.44	0.800 × 0.057	29
19.05 × 1.59	0.750 × 0.0625	27
13.00 × 2.50	0.511 × 0.098	37
20.00 × 3.25	0.787 × 0.128	41

(*Continued*)

Table 2.11 (Continued)

Size of hole mm	Size of hole in	% Open area
19.84 × 3.96	0.781 × 0.156	42
19.05 × 4.75	0.750 × 0.187	45
15.87 × 6.35	0.625 × 0.250	47
20.00 × 8.00	0.787 × 0.314	49
Diagonal slots		
12.29 × 0.50	0.484 × 0.020	14
12.29 × 0.62	0.484 × 0.024	19
11.91 × 0.73	0.469 × 0.029	12
11.91 × 1.07	0.469 × 0.042	25
20.62 × 1.09	0.812 × 0.043	27
9.90 × 2.38	0.390 × 0.093	27
11.91 × 3.17	0.469 × 0.125	37
12.70 × 3.96	0.500 × 0.156	36
12.70 × 1.04	0.500 × 0.041	28
20.00 × 2.00	0.787 × 0.078	29
11.50 × 1.50	0.454 × 0.059	24
19.05 × 3.17	0.750 × 0.125	40
Triangular holes		
3.17	0.125	26
5.00	0.197	15
6.50	0.256	26
9.52 × 11.11	0.375 × 0.437	16
Oval holes		
7.00 × 3.00	0.276 × 0.118	32
9.00 × 4.25	0.354 × 0.167	38
9.00 × 5.00	0.354 × 0.197	45
14.00 × 6.00	0.551 × 0.236	46
13.50 × 7.00	0.531 × 0.276	45

The punched holes need not be circular: various standard forms of perforated metal sheets are shown in Figure 2.14. The effective screen area of a strainer with one of these configurations is defined as the total area of the holes only. For simple straining duties, such as a pipeline strainer, the screen area should exceed the cross-sectional area of the pipe or of the entry it serves in order to avoid undue restrictions of flow. In practice this means the finer the perforations of the screen the less the effective screen area per total unit area, and in consequence the greater the total surface area of strainer required. This can be realized by increasing the diameter of the strainer until the effective screen area is at least equal to that of the entry area, or equally by making the strainer in a can or cylindrical shape to achieve the required minimum effective screen area.

Certain limitations are also imposed by the materials of construction. Thus whilst close-spaced 0.5 mm diameter holes are practical in brass, the minimum hole size with aluminium or monel is normally 1.5 mm. If finer straining is required with these materials then a mesh woven from the appropriate metallic wire would have to be employed or specially drilled plates used.

With punched holes it is generally impractical or at least uneconomical to produce holes that are smaller in diameter than the thickness of the plate. This restriction is removed if the holes are drilled, which then offers the possibility of producing small openings in plates whose thickness can be selected on strength requirements. Also drilling can be used for metals that are too hard to be punched. Further, to reduce flow resistance and eliminate clogging, conical or stepped holes can be drilled in a thicker plate as shown in the profiles of Figure 2.15.

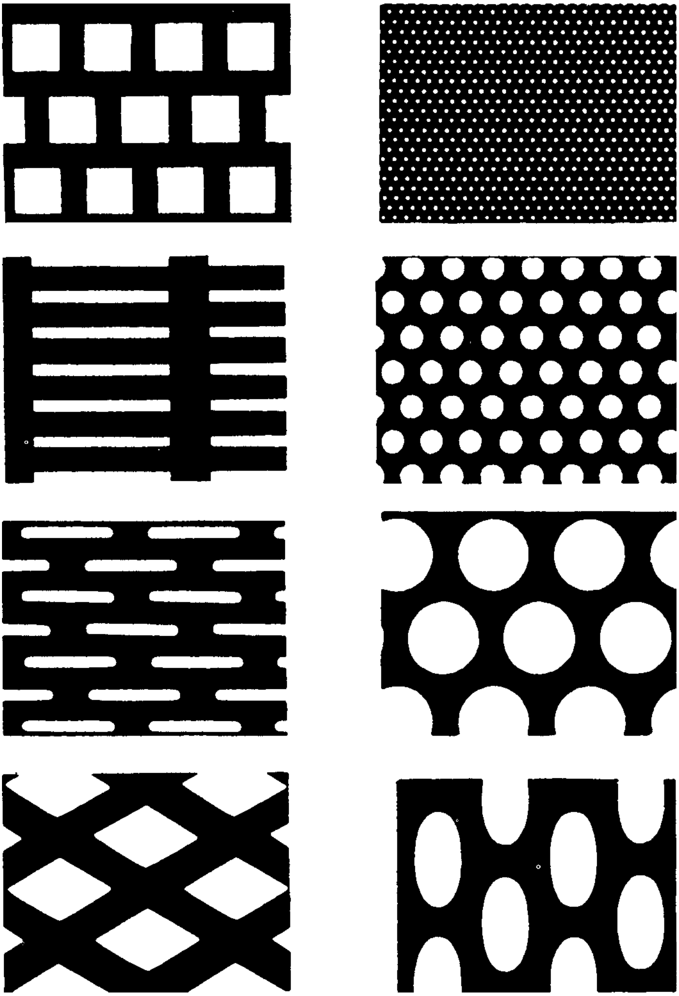


Figure 2.14 Typical perforated plate patterns

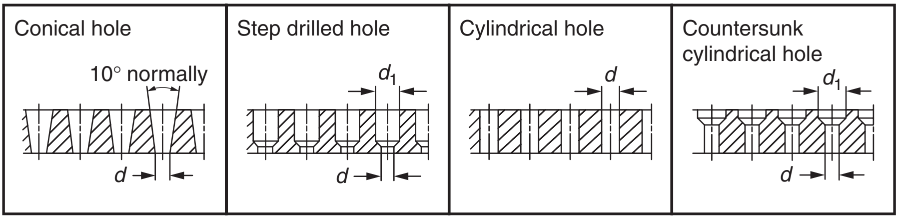


Figure 2.15 Drilled plate profiles

Where greater robustness is required, or where there are special requirements for handling the product, plates with slots rather than holes are widely used. These may be punched (in thin plates), cast (in thick plates) or milled. Milling is particularly suitable for producing thin clean slots, which may be further finished by electropolishing if required. Examples of some slot profiles as used on milled plates are given in Figure 2.16.

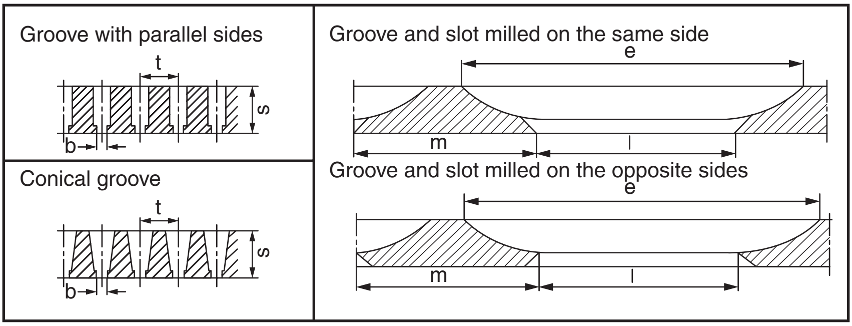


Figure 2.16 Milled hole profiles

Very fine holes or slots in flat sheets can be made by electrolytic processes, although the open areas are also small for the finer sizes of perforation. The processes involve either photo-etching or electroforming. Photo-etching involves the removal of metal from a continuous sheet on which a photomask has been deposited to protect some areas and allow others to be eroded, while electroforming creates the perforated sheet by building up a layer of metal by depositing it upon a similarly patterned substrate.

Expanded metal sheets

Expanded metal is made from a metal sheet by a repetitive process that involves first cutting it to form a series of short slits, and then stretching the sheet to open up these slits into the characteristic diamond apertures (Figure 2.17). This may be followed by calendering (pressing between rolls) so as to flatten the resultant metal strands from the sloping profile imposed on them during stretching. This format is widely used for structural material, and its main use in filtration is as cylindrical cores upon which other media are laid or moulded, or as supports for flat pads of fibrous media.

Bar and wire structures

A quite different use for metal in making filtration media comes in the structures that are built up from individual bars, rods or wires that may have been processed

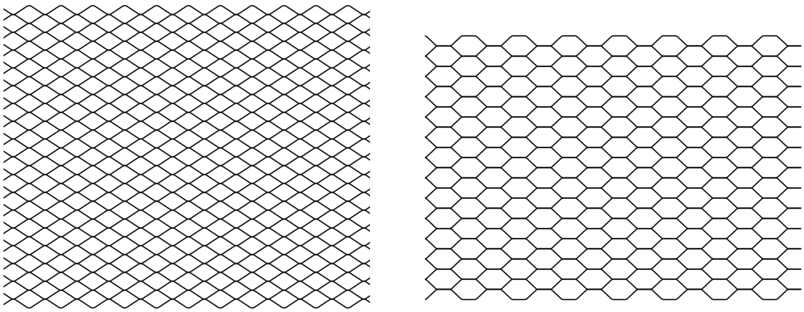


Figure 2.17 Expanded metal pattern

to change their shape. The filter elements made from these media are thus assembled rather than produced in sheets or rolls. As a result they are more expensive on a unit area basis than woven mesh or perforated sheet, and so are used where their particular combination of strength and accuracy of aperture size is necessary.

A screen surface can be formed by assembling a number of separate flat or round bars. The huge flat or sloping screens (grizzlies) used for separating crushed ores in mineral processing works are often made in this way.

Thick wires or rods can be moulded into a trapezoidal cross-section, with two parallel sides of unequal length, and two sloping sides joining them. If these ‘wedge wires’ are then mounted parallel to one another, with their wider flat faces adjoining but not quite touching, a very effective screen is formed. This can be arranged flat or in a cylindrical shape (as in Figure 2.18), and the widening spaces behind the front face ensures the minimum of clogging.

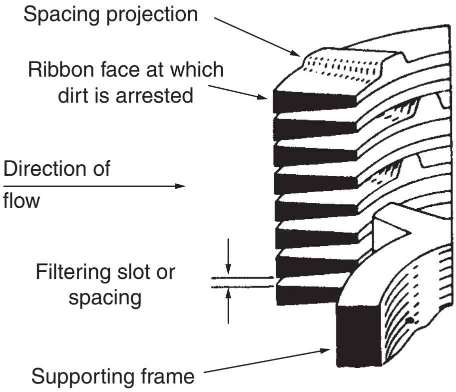


Figure 2.18 Wedge-wire screen

A particular form of wedge-wire screen is the *sieve bend* used in the wet classification of slurries. The screen is mounted vertically, with a surface that is flat across the screen, but concave downwards from a vertical portion at the top. The wedge-wire bars are arranged across the screen, with slurry flow downwards across the face of the screen, and almost tangential at the top. This filter can be used as a classifying device, separating fine solids from coarse.

2E. CONSTRUCTED FILTER CARTRIDGES

The majority of the specific filter media discussed so far in this Section have been porous materials, usually continuous in original format, with an intrinsic porosity consequent upon their method of original manufacture. Somewhat like the assembled bar types of media described in Section 2D, there is a very useful group of filter elements that are made up from individual pieces that, in themselves, have no filtration capability but, when appropriately assembled into a cartridge element, can prove very effective as filters and strainers.

In many of these types of filter, as assembled, they present a filtering surface at the outer face of a cylinder, with the method of assembly having created a series of apertures of controllable width. Filtration occurs very largely at this outer face, which can thus be considered as pure surface filtration. It also allows easy cleaning by the passage over this outer face of a brush or scraper, to remove collected dirt, and this can be done with the filter closed off from the fluid flow, or while filtration is actually occurring (thus making an automatic strainer).

Edge filters

Edge filters involve the use of cartridge elements where the element is composed of a stack of discs or washers of paper, felt, plastic or metal, clamped together in compression. Liquid flow takes place from the outer edge inwards between the discs, which may be in intimate contact in the case of non-rigid disc materials, or through the controlled clearance space between individual discs, provided by spacing washers.

Such a construction has the advantage that the collected contaminant can be scraped from the upstream surface more easily and completely than it can be from a screen, and this cleaning can be performed during operation of the unit. In addition, this type can be manufactured with inherent self-cleaning properties, so that cake build-up on the upstream surface can be virtually eliminated.

An edge filter element employing stacked paper discs is shown in Figure 2.19. The pack of discs is held under compression by springs at the top of the assembly, so that the liquid undergoing filtration can only pass through the minute interstices between the discs in layers of near molecular thickness. Virtually all solid impurities are, in fact, left on the edge of the discs since such an element can be capable of yielding an absolute cut-off of 1 μm or less.

A further property of such an edge filter, employing unimpregnated paper discs, is that it can trap and retain finely dispersed water in fuels, oils or similar fluids. It is even possible to remove dissolved water by the provision of moderate heat and

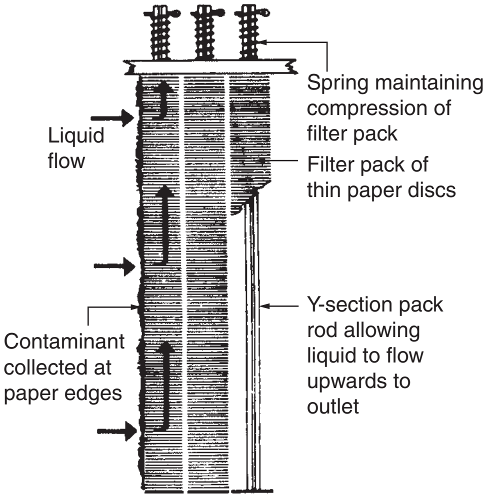


Figure 2.19 Stacked disc edge filter

vacuum. The presence of water will, however, substantially increase the back pressure of the filter due to the swelling of the discs, further restricting the clearance space available for flow. This can, if necessary, be used to operate a warning device that water is present in the fluid being filtered.

It will also be appreciated that whilst the performance of such a paper element is often better than that of a pleated paper element, its normal resistance, and thus back-pressure is very much higher, or, size for size, its capacity is appreciably less. However, it is one of the best types of filters for removing very fine solids from liquids, even colloidal graphite from oils. It is virtually immune to the effects of shock pressure and its element life is long, with a minimum of maintenance requirements. Cleaning can usually be accomplished quickly and efficiently by a reverse flow of compressed air. The ultra-fine filtering properties may inhibit its use for particular applications due to the build-up of ultra-fine solids, restricting flow where very fine and frequent cleaning is impractical.

The edge filter is thus mainly made of individual rings or discs stacked together, with spacers between them as required, or with dimples on the face of the disc to provide a flow channel. The same effect can be achieved by the use of a continuous helical ribbon or flat spring compressed together to give the required spacing between consecutive turns.

Stacked disc filters

Similar to the edge filter in appearance, in that it has an array of disc-shaped components held on a central core, the stacked disc filter differs because the discs are actually hollow, with filter media over the faces of the disc. It employs individual discs, porous on both sides – that are stacked over a perforated inner tube – with intermediate spacing washers creating a flow space between each pair of discs.

Flow is between and subsequently through the filter discs and into the inner tube. The discs typically have a fine metal wire screen supported on a coarser back-up screen to provide effective use of the full filtration area. The complete disc assembly is then clamped together inside an outer, cylindrical straining screen that prevents passage of larger particles into the spaces between the discs.

Performance is nominally that of the mesh elements or filter screen apertures, typical standard openings being from 0.25 to 0.025 mm, equivalent to ratings of approximately 250 and 25 µm respectively. With this form of construction, however, performance materially improves as dirt collects on the screen surfaces, providing increasingly finer filtration.

This particular form of filter is thus a mesh aperture controlled one, rather than an edge type. It does provide a large surface area in a compact volume, with a moderately low pressure drop.

Yarn-wound cartridges

A completely different constructed cartridge has a perforated cylindrical core around which is wound a continuous filament or yarn. With a plastic filament or metal wire, the core may be threaded and the first layer of the filament is wound into the threads, giving the required degree of spacing of consecutive turns. The cartridge may have just one layer, when the effect is the same as an edge filter, or there may be several layers, which are usually at opposite angles, layer by layer, to give a component of depth filtration.

More commonly, a multifilament or staple yarn is used. This kind of cartridge is constructed by continuously winding the yarn in a carefully controlled open pattern around the central core, which is typically a perforated metal or plastic tube open at each end. Typically the matrix so formed has a graded structure with pores of decreasing size meeting the inward direction of flow – a gradation achieved by differing degrees of tightness in the windings. Cartridges are based on a wide variety of yarn materials embracing both natural and synthetic fibres. The yarns used are mostly spun from short staple fibres, the fibrillated surface of which is brushed or teased to produce a fuzzy surface or nap, which contributes importantly to the filtration mechanisms. If monofilament yarns are used, they are generally texturized or crimped in some fashion before being formed into a cartridge.

Despite its early origin, in the 1930s, the 63 mm diameter × 250 mm long yarn-wound cartridge continues to be widely used in many sectors of industry. Its simple construction, and its convenient versatility in use, resulted in its becoming an unofficial standard as increasing numbers of manufacturers competed for a large and growing market. It also effectively served as a prototype in respect of size and dimensions for the diversity of styles of cartridge developed in more recent years.

The filtration characteristics of a yarn-wound cartridge depend on the type of yarn used as well as on the way it is produced and wound. Filtration within the interstices of the yarn is as important a mechanism as filtration in the spaces between the consecutive turns.

2F. MEMBRANES

In terms of filtration and separation technology, membranes have become one of the most important components. It is almost impossible to separate membrane media from the processes and equipment in which membranes are used, so this is only the briefest of introductions to membranes, with more detailed coverage in Sections 3 and 4.

In separation terms, membranes were developed as thin, flexible semi-permeable sheets of regenerated cellulose material, intended to separate species at the molecular and ionic level, their first main application being in the purification of salt and brackish waters by reverse osmosis – which is not a filtration process, but one relying on different rates of diffusion for water and ions through the membrane material under high transmembrane pressure.

The word 'membrane' has stuck to a range of separation media that has expanded enormously from this early form, to embrace solid inflexible inorganic materials, especially ceramics, and an ever-increasing group of polymeric materials, and to applications that now extend through ultrafiltration into the microfiltration range. The existence of the membrane as a very effective filtration medium led to the development of the whole field of cross-flow filtration, which also now extends well beyond its reverse osmosis origins.

Membrane types

As the term is applied nowadays, membranes can be porous or non-porous, polymeric or inorganic. They can be used for a range of separations including solids from liquids, liquids from liquids, and gases from gases, but in particular it is the filtration of micrometre and sub-micrometre size particles from liquids and gases where membranes have proved their worth in the filtration business.

Over recent years, membrane technology has been carried into many industrial sectors, including the chemical, petrochemical, food and beverage processing, pharmaceuticals, electronics, biotechnology and especially the treatment of water. In basic terms, there are three broad types of membrane material:

- the modified natural products based on cellulose
- the synthetic polymer materials, such as polyolefins, polyesters, fluoropolymers, and
- the generally inorganic materials, such as ceramics.

There is also the developing field of dynamic and liquid membranes.

To be effective in filtration and related separation processes, membranes must be chemically resistant to both the feed and cleaning fluids, they must be mechanically and thermally stable, they should have high permeability whether for particles or ions or molecules as appropriate, they should be highly selective, they should be stable in operation for prolonged periods, and they should be strong enough to resist the high transmembrane pressures necessary for some membrane processes.

When particle separation through a membrane is being considered, the size of the hole through which the particle is going to move, or by which it is to be retained, becomes one of the important characteristics. A membrane with pores in the region of 0.005–1 μm in diameter would be called a *porous membrane*. With pores smaller than this, say 0.001–0.005 μm (1–5 nm) in diameter, this will be called a *microporous membrane*. Holes of 1 nm or less cannot be regarded as true pores but merely spaces that open up between molecules of the membrane material, produced by the random movement of these molecules, so that a diffusion process rather than particle movement is the process that is characteristic here, and such a membrane will be called non-porous, or semi-permeable.

A membrane that has the same chemical and physical structure throughout its thickness in the direction of travel of the separating species is called a *symmetric* or isotropic membrane. If it has a different chemical and physical structure in the direction of its thickness it is called an *asymmetric* or anisotropic membrane (see Figure 2.20). The most common form of asymmetric membrane has a very thin skin of highly selective material, supported on a much thicker substrate, usually made from the same material, but quite possibly of different materials. If the materials are the same, then the asymmetric structure is usually created in one piece with the thin active skin.

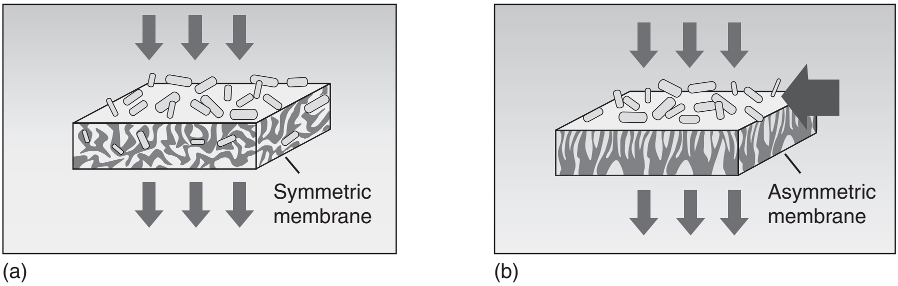
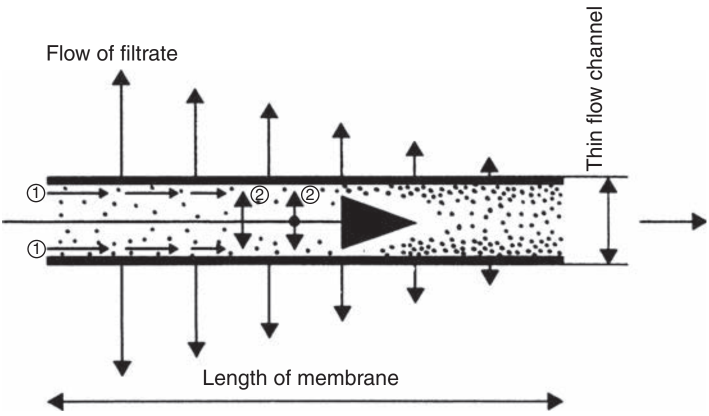


Figure 2.20 Symmetric (a) and asymmetric (b) membranes

A key feature of membrane processes is the ease with which the surface of the membrane becomes blocked with very fine, slimy material. This is called *fouling* and membranes systems are usually designed with very great care such that the fouling process is minimized as far as possible. The actual membrane surface can be chemically modified to decrease the tendency to foul.

A major development in filtration, which came with the first, reverse osmosis membrane process, was the fact that the flow of the fluid at the membrane surface is tangential to it, rather than perpendicular to that surface. This has become known as *cross-flow filtration* (see Figure 2.21), and almost all membrane processes now operate in crossflow rather than through flow mode. Further scouring action is achieved by having the membrane medium move relative to the liquid flow, either rotating close to a stator, or vibrating.



① Tangential force sweeping over the membrane surfaces

② Filtration pressure (decreases along the length of the membrane)

Figure 2.21 Cross-flow filtration

Membrane module formats

Membranes are made in a variety of ways, according to how they are to be used, with basic formats as flat sheets, tubes of very different diameters and solid blocks, on the surfaces of which the membrane is later deposited. The various manufacturing processes can be broadly summarized as:

- sintering of fine graded particles into a variety of shapes (the most common method for ceramic membranes)
- solvent casting or phase inversion, involving the dissolution of the basic polymer in a solvent (or mixture of solvents), followed by the addition of another solvent to precipitate the polymer, and careful evaporation of the solvent, to make sheet membranes, or, after extrusion, hollow fibres and capillaries
- the spinning of very fine fibres (of any basic material) that are laid down as a thin web on a strong porous substrate
- the irradiation of an impervious film, followed by its etching to remove the material from the tracks of the irradiating particles (‘track etching’), and
- forming the polymer into a very thin but impervious film, which is then dimpled all over, and stretched laterally to break the film at each dimple to cause multiple ruptures.

Membranes are also made by the photo-etching of metallic sheets, although with a very low proportion of open area.

A piece of membrane material that is to be made into a filter medium must be held secure in some way, and sealed into a housing so that there is no chance of liquid leakage from one side of the membrane to the other, under the force of the high transmembrane pressure. Most membrane media are used in some form of module, which can be easily inserted in the housing, and removed from it again for exchange or cleaning. Membrane modules are of very different designs and include:

- *flat sheets* that are held in a structure like a plate-and-frame filter press, with sheets mounted back-to-back in pairs; liquid feed flows across the sheets on the inlet sides, while permeate flows through each sheet to a joint outlet between them
- several of the membrane material manufacturing processes can produce sheets like paper or thin card, which can then be pleated; if this pleated sheet is fastened to a cylindrical core, then a *pleated cartridge* is formed, which is an increasingly important format for microfiltration membranes, with quite a high surface area inside a cylindrical housing (although not able to withstand a very high trans-membrane pressure)
- long flat sheets that are laid in a pile with appropriate spacers and supports between the sheets up to the required total thickness; the pile of sheets is then rolled up tightly, from one of its shorter sides, to form a cylinder, which is then inserted into a cylindrical housing vessel – this is the *spiral-wound* format; there is a central porous core to which the ends of the membrane sheets are sealed, and permeate flows through the membranes into alternate spaces and around the whole roll to leave through this central permeate tube; meanwhile, feed enters at one end of the cylinder, flows between the other pairs of turns, to leave as concentrate (or retentate) at the other end of the cylinder (see Figure 2.22)

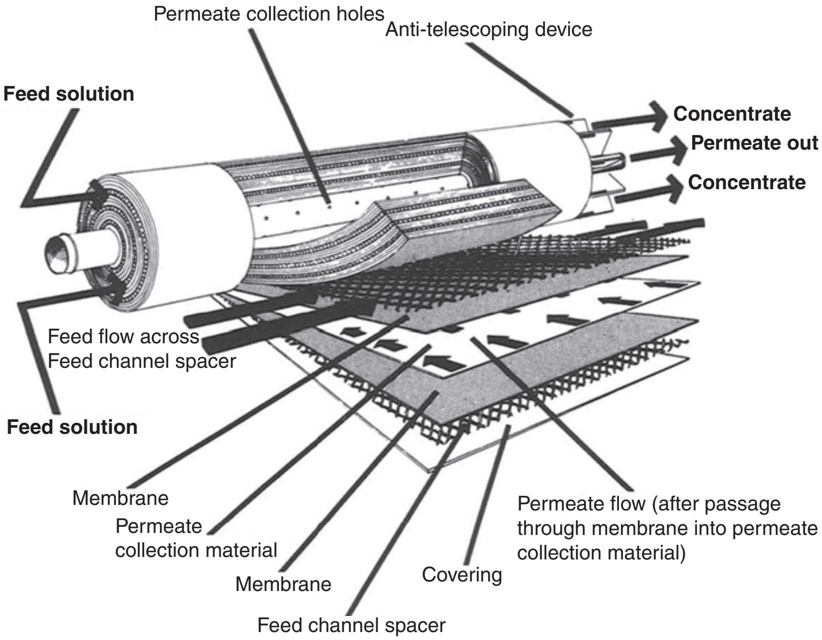


Figure 2.22 Spiral-wound membrane module

- *tubes* of membrane media, ranging from a few mm up to 25 mm in diameter, are little used outside the laboratory, because of their low surface area, but are found on the practical scale bundled together like a shell and tube heat exchanger, welded at each end into a tube plate, and enclosed in a cylindrical shell
- with a similar structural principle, the *hollow fibre* module has a hundred or more long hollow fibres, each with an internal diameter of 3 mm down to 0.5 mm or less, bundled tightly together and sealed at each end into a resin plug; the bundle may be straight, or, more usually, folded in half, with inlet and outlet at the same end of the bundle; liquid flow is from outside the fibre to its inside, the small diameter enabling high transmembrane pressures (and it was in this format that the earliest reverse osmosis membrane modules were made), and
- *capillary tube* modules use tubular membranes somewhat larger than hollow fibres in diameter, again bundled into resin plugs at each end, but almost always used unfolded in their cylindrical housing, and with liquid flow from inside out.

The earliest membranes were of a single material all the way through, whether symmetric or asymmetric. Nowadays, membranes have been developed with a composite structure, where the base of the membrane is a material providing strength to the membrane, while the surface is a thinner layer of another material, conferring high quality of filtration to the whole structure. The two (or even more) different layers may be combined by lamination or by coating the finer onto the coarser substrate.

The full range of membrane formats described above can be found with polymeric materials, but an increasing range is also available with inorganic media, especially ceramic materials. The standard method of forming a ceramic membrane is to make the basic structure from relatively coarse sintered particles, with appropriate flow channels in the structure, and then to lay down a thin layer of fine particles to provide the membrane, which is sintered onto the separating surface. A typical format made in this way, the monolithic block, is illustrated in Figure 2.23. The cylindrical holes formed in the block make the separating surface, on which the membrane is formed, and the block is held in a cylindrical housing. Other ceramic membranes include tubes and sheet formed from ceramic fibres, which can be sufficiently flexible to be pleated.

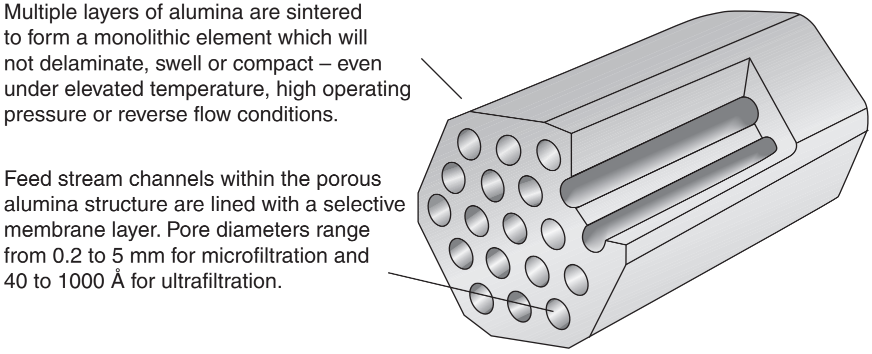


Figure 2.23 Ceramic monolith

Metallic membranes are usually formed on a substrate of woven wire mesh, onto which the membrane is laid, either as a sintered layer of fine metal powder, or, in fact, as a metal oxide (and thus, technically being a ceramic membrane). Membranes made from stainless steel and aluminium are in industrial use. Pore sizes of these membranes can be from 2 μm up to 100 μm.

Membrane processes

Membrane separations began in the 1960s as an alternative means to distillation for the desalination of salt (i.e. sea) and brackish waters. This was called *reverse osmosis* because it works by applying a transmembrane pressure greater than the natural osmotic pressure between the two solutions (seawater, say, and desalted water).

The various processes in which membranes are now used began with reverse osmosis, which, of course, is a diffusion process, in which water molecules move through the non-porous membrane, leaving the ions and other impurities behind. This is a high pressure process, needing 30–60 bar. In recent years, the 'tightness' of reverse osmosis membranes has been relaxed, to extend the diffusion separation range (see Figure 2.24) to allow passage of some ionic and molecular material, a process called *nanofiltration*, which needs correspondingly lower transmembrane pressures (20–40 bar). True filtration is achieved at the smallest particle sizes with *ultrafiltration*, which is used for the separation of large organic molecules, and colloidal solids, at pressures in the region of 5–10 bar. Membranes really entered the filtration field with the arrival of *microfiltration* membranes, operating at only a few times ambient pressure. The lower pressure drops of ultrafiltration, and especially microfiltration, enable separation with very much lower energy demands.

The microfiltration membrane is a porous one, which has the largest pore diameters among the various types of membrane. It aims at separating particles with diameters in the range of about 0.03 to 10 μm (although microfiltration using other media than membranes will be used up to perhaps 100 μm). This membrane separation process utilizes pressure differentials in the region of 1–5 bar, much lower than the pressures required in the diffusion-controlled processes. Microfiltration membranes are being increasingly used for the separation of very fine particles, especially in sterilization by the removal of bacteria. They are being used in a wide range of applications, and also as prefilters for ultrafiltration systems.

Ultrafiltration membranes are microporous, with a separation range from about 0.005 μm to about 0.1 μm (5 to 100 nm), which is roughly the size range of virus particles, so that ultrafiltration is fast becoming the last step in water purification. The process operates at pressure differentials of 5–10 bar, still well below those of reverse osmosis and nanofiltration. Ultrafiltration is used also for the separation of large organic molecules, and its capabilities are then measured by its molecular weight cut-off (MCWO) potential, enumerated in Daltons (or kD for the largest molecules). Just as microfiltration membranes are being used as prefilters for ultrafiltration, so is the latter being employed as prefiltration for reverse osmosis.

Reverse osmosis is the process of choice, certainly where energy is cheap, for the production of drinking water from salt water. It, and nanofiltration, are both

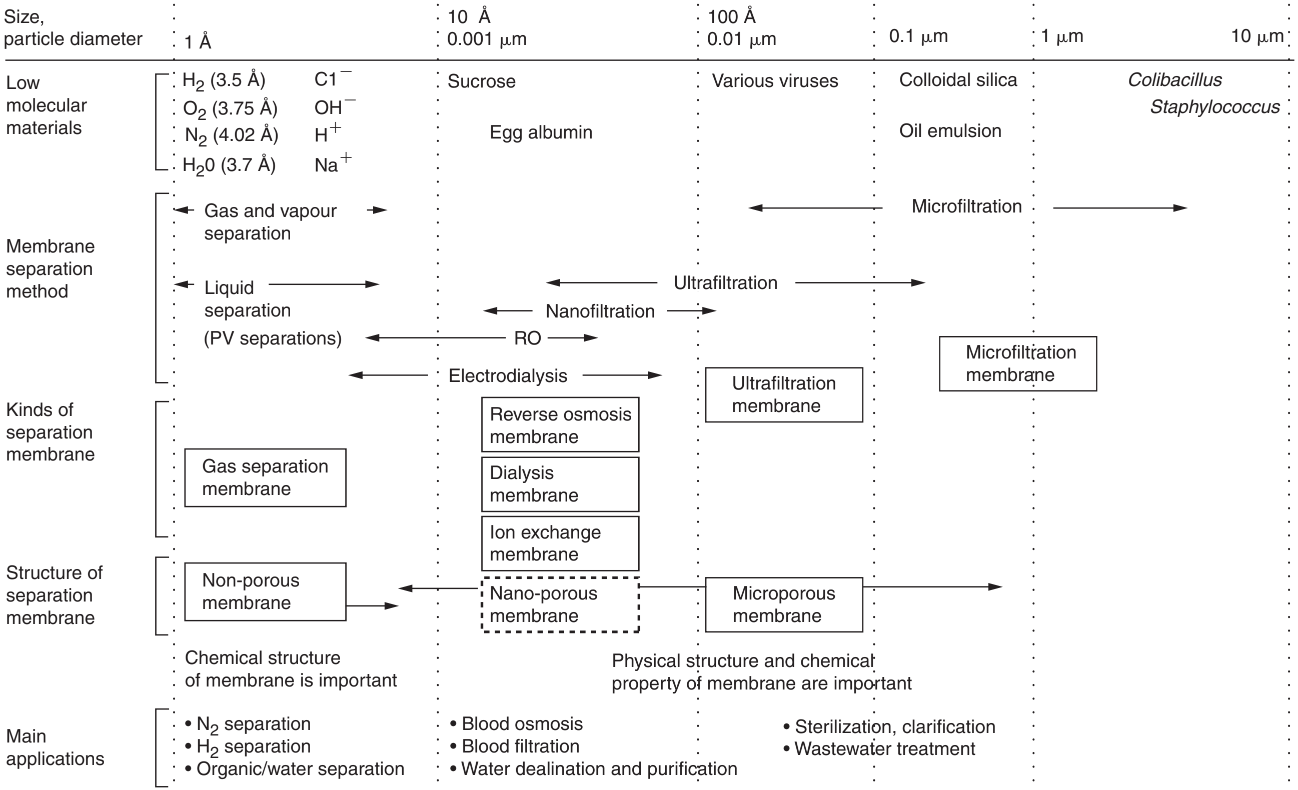


Figure 2.24 Membrane separation technologies

diffusion operated processes used to separate solvent (mostly water) and some ions from a solution. They are being increasingly employed in industrial separations and clarifications.

Other liquid separation systems using membranes include *dialysis* and *electrodialysis*, where the driving force is now a concentration difference between the two sides of the membrane. The main use for dialysis is in blood processing, as a kidney replacement or booster, but both processes are also being used industrially, electrodialysis especially in desalination.

Membranes are also found in gas or vapour separations. *Pervaporation* is used to separate one vapour component from a liquid mixture, by diffusion of the selected vapour through the membrane, to a lower pressure on the downstream side. This is particularly useful for achieving otherwise difficult separations, such as of an azeotropic mixture. *Gas separation membranes*, which also operate by diffusion, are becoming a major processing tool. A significant proportion of air separation plants (into oxygen and nitrogen) now achieve the separation by membranes, as do plants for recovering hydrogen and helium from petroleum refinery off-gases.

The membrane processes that have just been briefly described can be implemented, in principle, with any material (cellulosic, synthetic polymer or inorganic) or in any format (hollow fibre, spiral wound, etc.). The system design process selects the most appropriate material and format according to the process operating parameters.

The membrane processes are characterized by quite small flow channels in and through the modules. This means that adequate prefiltration must be employed, in order to ensure as long a life as possible for the final separation stage. It is not uncommon now to find, for example, an ultrafiltration plant (with its own inlet microfilters) being used as a prefilter for a reverse osmosis desalination plant, as illustrated in Figure 2.25.

2G. PACKED BEDS

The forms of filter media discussed in the previous parts in this section have all been constrained as pieces of material or structures. The remaining group of media materials, of particular interest to clarifying processes, are unconstrained (except by the walls of their containing vessel), being masses of coarse particulate substances, used as packed beds within which contaminants are removed by what can truly be called depth filtration.

Deep-bed filtration involves filtration vertically through a packed bed of granular or fibrous material, whose height is considerably greater than even the thickest of continuous filter media. It is typified by the conventional sand filter, which clarifies water by depth filtration mechanisms as it flows through a bed of graded sand that may be up to one metre in depth.

Deep-bed filters are of very simple construction: a vessel (usually cylindrical), a supporting grid at the base of the vessel, and the bed of granules – plus the necessary inlet and outlet piping. Effectively, the medium is the filter.

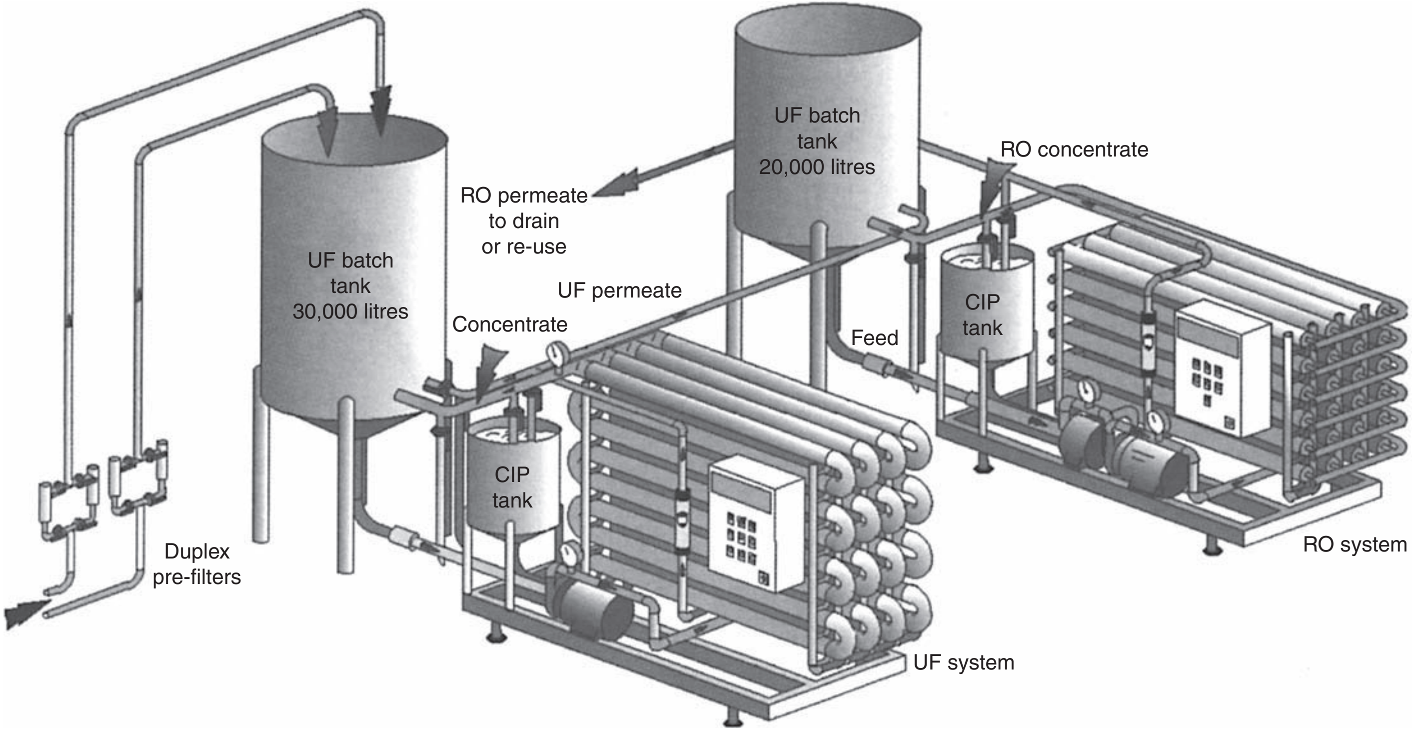


Figure 2.25 A combined UF/RO membrane plant

Deep-bed media

The media used in deep-bed filters must be inert, resistant to fracture yet easily prepared in batches of graded particle size. Many different granular and crushed materials have been used to form the deep beds employed in the large gravity and pressure filters common to the water purification and sewage treatment industries. In addition to sand, which is the classic and most common material, others used include garnet, ilmenite, alumina, magnetite, anthracite and quartz; coke and pumice have also been used but, because of their porosity, they are troublesome to clean and consequently give rise to the danger of uncontrolled breeding of bacteria.

The suitability of a granular material for use in a deep-bed filter depends both on the application and on the type of filter. Conventionally, there are two main types that operate with gravity flow downwards through a 0.6–1.0 m deep bed; these are identified respectively as 'slow' and 'rapid' sand filters, but only the rapid variant is truly a deep-bed filter. These utilize a velocity of 5–15 m/h and function by depth filtration within the bed. They are cleaned frequently by cessation of process flow, followed by a reverse upward flow of wash water at such a rate that the bed expands and releases the trapped dirt particles; this cleaning flow may be augmented by some form of agitation, such as injecting compressed air below the bed or hydraulic jets impinging on the surface. This cleaning process has an important secondary effect, which is to reclassify the granules of the bed based on the combined influence of their size and their density, so that the washed bed is graded from finest at the top to coarsest at the bottom.

A size classification of one material does give the finest particles at the top, and therefore is more easily clogged than if there was a decrease in the size of flow channels downwards through the bed. The proper reclassification is best achieved by using a multi-layer filter. Two or more materials of different densities and sizes make up the bed, so that the hydraulic classification of cleaning places the finer, denser particles below the coarser, less dense particles (with filtration flow downwards).

The most modern version of the rapid sand filter is that which uses a moving bed of sand, whereby both filtration and cleaning proceed continuously and simultaneously. Recent evidence suggests that such filters can be as effective as membrane filtration plants in the removal of such pathogens as *Cryptosporidia* and *Giardia* from water intended for drinking.

Anthracite is usually one of the materials in a multi-layer bed. The anthracite particles are lighter and larger than sand particles, such that a mixed bed of the two provides good filtration in depth. The larger spaces between the anthracite particles enable high flow rates to be achieved, with low pressure drop losses, while the large surface area of the anthracite is efficient in removing algae, bacteria and turbidity.

Precoat filtration

Quite closely related to deep-bed filtration in principle is precoat filtration, which uses a bed of inert solids formed on the upstream surface of a relatively coarse filter medium to act as the actual medium. The most popular solids for this purpose are kieselguhr (diatomaceous earth) and perlite. These can only be used where the collected solids are not wanted for subsequent treatment.

Kieselguhr is also used as a filter medium in its own right, again for clarification duties, being used by itself or in combination with cellulose fibres, as in the filter sheets used for beer clarification.

3

TYPES OF FILTER

SECTION CONTENTS

3A. INTRODUCTION

This first main section of the Handbook, which deals with filtration equipment, consists of a number of areas, each devoted to a type of filter. In accordance with the main theme of the book, more attention is paid to those filters used for clarification of gas or liquid streams than to those designed for solids recovery from fluid suspensions, although sufficient is included about these latter so that they can be seen in their context.

The complete spectrum of filtration equipment is shown in Table 3.1, together with a correlation with the chapters of this section. The classification of Table 3.1 includes a few items that are on the fringe of filtration as it is being interpreted here, and these items: demisters, scrubbers, and filter coalescers are covered separately in Section 7.

Table 3.1 is organized primarily by the type of filtration used in each filter. Relatively pure surface filtration comes first, exemplified by screens, followed by depth filtration. The bulk of the table is taken up with those filters that work initially by surface screening, but which move quickly into the formation of a cake of accumulated solids on the surface of the filter medium. Once a thin cake is formed, the remaining filtration occurs through this cake, which grows in thickness until the pressure differential across it becomes too great.

Table 3.1 Classification of filters

C	Screens
B	Stationary
	In-line strainers*
	Horizontal or slightly inclined
	Curved ('sieve-bend')
	Vertical
	Moving
	Continuous (vertical, or rotating drum)
	Oscillating (vibrating or gyratory)
	Demisters**
	Scrubbers (wet and 'dry')**
	Depth filters
J	Pads and panels (cassettes)*
L	Thick cartridge*
V	Deep bed ('sand')*
	Surface/cake filters
	Vacuum
	Batch
D	Nutsche (manual or scroll discharge)
E	Rotary table
E	Tilting pan (single or rotaining/indexing)
N	Leaf or tubular element
	Continuous
F	Rotary drum (range of discharge mechanisms)
G	Rotary disc
	Indexing disc

(*Continued*)

Table 3.1 (Continued)

H	Belt (single or multiple chambers)
	Gravity
H	Flat bed (roll)*
I	Centrifugal
	Fixed bed (batch and semi-continuous, perforate basket)
	Manual discharge
	Automatic discharge (vertical, horizontal, inclined axis, inverting)
	Moving bed
	Conical screen (horizontal or vertical axis)
	Free (tumbling) discharge
	Controlled discharge
	Cylindrical screen (horizontal axis – pusher)
	Fluid pressure
	In-line
B	Basket strainers
	Sheets*
	Capsules*
K	Bags, sleeves and pockets*
L, M	Cartridges (thin medium – wide range of designs)*
S	Other membrane filters (spiral wound, tubular, etc)*
	Pressure vessel
	Tubular element (bag or candle filter)*
	Filter coalescers
	Flat elements (sheet, plate, leaf)
	Thickners
F	Rotary (drum, submerged drum, Fest, etc)
O	Filter press
	Simple plate and frame
	Chamber press diaphragm plate, plate press)
	Tower press (continuous medium)
Q	Variable volume (tube press)
	Mechanical pressure
P	Band press
	Horizontal
	Vertical
R	Screw press
	Other force fields
T	Magnetic
U	Electrically aided

Notes: This list is mainly of equipment used for liquid phase separations, except for those items marked:

** gas filtration only or mainly

* versions for gas and liquid filtration

Letters on left denote chapters in Section 3.

The cake filters are divided by the driving force that causes the filtration: vacuum (i.e. a negative pressure at the filter medium), gravity alone (i.e. the hydrostatic head of the liquid above the medium), centrifugal force (i.e. an amplified gravity effect), fluid pressure (imposed by the suspension feed pump), mechanical pressure (a squeezing effect), and the use of other force fields. The large number of types of pressure filter is obvious – for most people the pressure filter, from simple cartridge to the complex fully automated filter press, typifies filtration.

Notation is also made in Table 3.1 of which filtration equipment items are intended mainly or totally for gas filtration, and which, suitably designed, can be used for both fluids. It can be seen that the range of gas filtration equipment is much smaller than that for liquids. This is because the recovery of solids from a gas suspension is a task not often undertaken in a filter, a cyclone being used instead (and covered in Section 7). Gas filtration is almost always a decontamination process, whether it is of inlet air to buildings or machinery, or of exhaust streams from machines or processes. Solids recovery from liquid suspension, on the other hand, is a task frequently undertaken by filters, and the wide variety of types of liquid filter is almost entirely because of the problems imposed on filter design by the need to remove these collected solids from the inside of the filter.

It should be noted that the full spectrum of mechanical separations should include a number of sedimentation processes and their related equipment. These are also dealt with in Section 7.

The contents of Section 3 aim to describe the main types of filter, illustrating their methods of operation and key characteristics. Rather more space will be given to the process, solid recovery filters, because Sections 4 to 6 are almost entirely concerned with the chief applications for filtration of contaminants, and these sections will return to the relevant equipment as well.

This Handbook has a descriptive role and is not intended to act as a textbook of filtration technology. For that function the reader is directed to: *Solid Liquid Separations* (2005), *Principles of Industrial Filtration* (2005), *Scale-up of Industrial Equipment* (2005), *Equipment Selection and Process Design* (2006) (all by R.J. Wakeman and E.S. Tarleton, Elsevier Advanced Technology); or *Solid-Liquid Filtration and Separation Technology* (by A. Rushton, A.S. Ward and R.G. Holdich, 2000, 2nd Edn, Wiley-VCH).

3B. STRAINERS

For a Handbook devoted to the removal of suspended contaminants, there is no better way to start than with the strainer, whose function is entirely that of protecting downstream items of equipment, or downstream processes, from the impact of impurities that may block narrow passageways or abrade sensitive surfaces.

Strainers offer a simple method for the protection of pipeline systems, by removing debris such as dirt, swarf, weld sputter, scale and so on. They are simple coarse filters using perforated plate or wire mesh as the filter medium. Strainers fall broadly into two categories: temporary strainers and permanent strainers.

It is true that many types of filter could act as a strainer but it is rare that the straining function (unless at very low cut-points) needs anything more complicated or expensive than the simple units described here.

Temporary strainers

Temporary strainers are intended for short periods of application, such as being fitted during the run-in period of a new system, or when restarting a pipeline system after shut-down and maintenance. They are intended to remove coarse debris particles present in the system. After a suitable period of use, they are removed (and can be cleaned and stored for future use).

Strainers of this type are normally designed with standard flange faces so that they can be fitted at a suitable flange joint in the pipeline. When removed they can be replaced by a spacer washer. These filters may take the form of a flat disc or a conical basket – some types of strainer basket are shown in Figure 3.1. Flat disc strainers are normally perforated plates, while basket strainers may be of perforated plate or supported wire mesh. Basket strainers can have a higher dirt capacity,

Figure 3.1 Strainer baskets

normally have a lower pressure drop, and can provide finer filtering (typically down to 150 µm).

Where fitting such strainers is difficult or impractical on a particular system, other types of temporary strainers are available to match a blind T-junction fitting, into which they can readily be fitted and removed. These strainers are often of a trough shape, and have become referred to as ‘bathtub’ strainers.

Permanent strainers

Permanent strainers are conventionally complete fittings, most commonly with a housing of Y-configuration, with a cylindrical strainer element (as in Figure 3.2). They can be used in both the horizontal and vertical planes, and are intended for applications where only a low concentration of contaminants is expected. The element is retained in its housing by a plug end, which may be plain or fitted with a valve that can be opened for blow-through cleaning. In either case, the element itself is removable and so this type can also be used as a temporary strainer. Typical data for the cut-points of wire mesh Y-type strainers are given in Table 3.2, while pressure loss data are included in Figure 3.3.

Figure 3.2 Y-type strainers

Table 3.2 Y-type strainers ratings with wire mesh

Mesh size	Rating µm
20 × 20	894
30 × 30	570
40 × 40	400
60 × 60	250
80 × 80	185
100 × 100	140

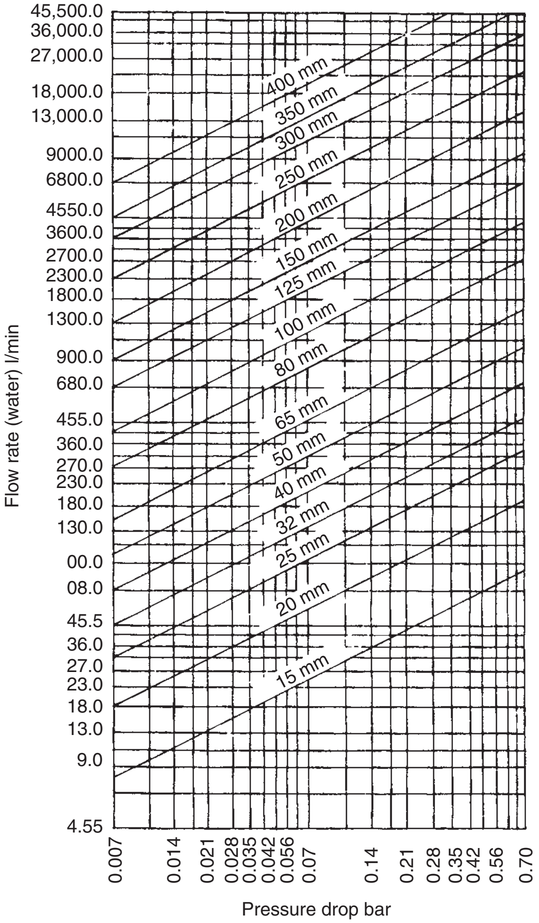


Figure 3.3 Y-type strainer pressure drops

Single basket-type strainers, such as that shown in Figure 3.4, with large filtration areas, are used for high flow debris collection in pipelines, and on the suction and discharge sides of pumps. They may be used in-line or off-line, and can be made of cast iron, cast steel, stainless steel or bronze, depending on the application required. Applications can include wastewater systems, boiler feed pumps, lubricating and fuel oils, refining of crude oil, fire protection duties, various marine applications, and in the process industry for the protection of flow meters, heat exchangers and pumps.

The principle advantages of basket strainers is that they can provide a greater dirt-holding capacity and can have easier access for removing the strainer for cleaning. They normally have a higher pressure drop than simpler Y-type strainers, as can be seen from Figure 3.5.

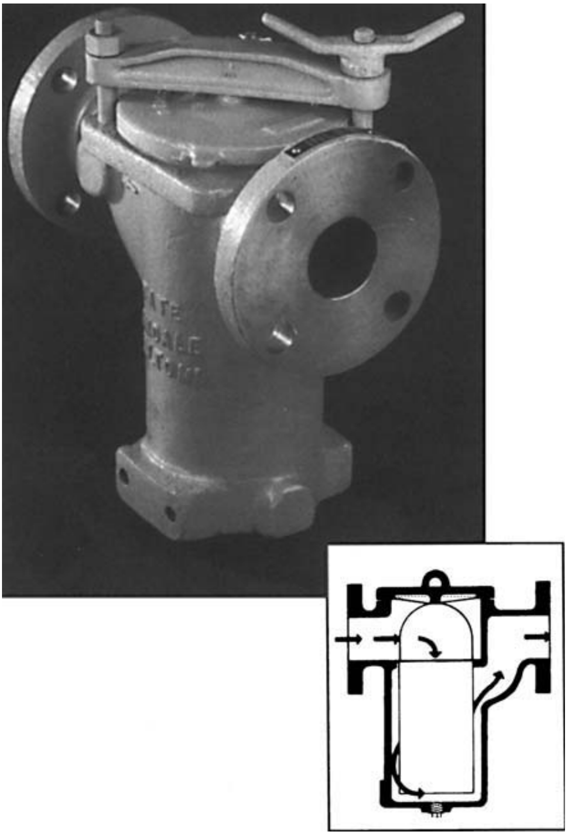


Figure 3.4 Basket strainer

Continuous operation

An obvious disadvantage of a permanent strainer of the types just described is the need to shut down the plant flow so that they may be cleaned. Where continuous operation is required in a pipeline service, duplex strainers can be used in an integral unit with the provision to isolate one element at a time for cleaning, or even having multiple strainers in one unit (as shown in Figure 3.6). Individual strainer elements or baskets are then made accessible via cover plates with static seals (usually O-rings).

The duplex or multi-basket strainer must still be watched to check for the need to swap baskets. Self-cleaning strainers may be used as an alternative to dual or multiple strainers where continuous operation is critical in the process system. Two methods of self-cleaning are illustrated in Figure 3.7 – one uses a brush and the other a scraper. Brush cleaning is suitable for most applications, with scraper types more specifically suited for handling high-viscosity products.

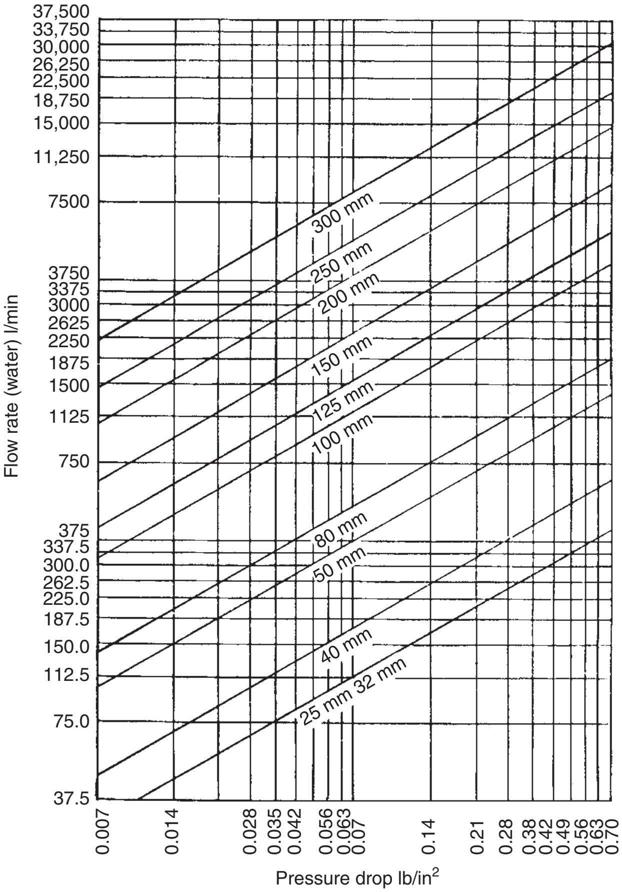


Figure 3.5 Basket strainer pressure drops

Performance

Perforated plate strainers provide coarse filtration down to about 150 μm. For finer filtering, wire mesh elements are normally used in conjunction with perforated plate or other form of reinforcement, when this is necessary for added mechanical strength. Wire mesh strainers can provide filtration down to about 40 μm, but with reduced strength due to the increasingly fine wire used.

Numerically, the service life of a strainer (between cleaning times) can be expressed in terms of the ratio of open area of the strainer to the pipe cross-section. Open area is determined by the choice of perforation or mesh, which would normally be of the order of 15–20%. Strainers are usually proportioned to provide a 3:1 area ratio for general service, although this may need to be doubled in the case of more viscous fluids.

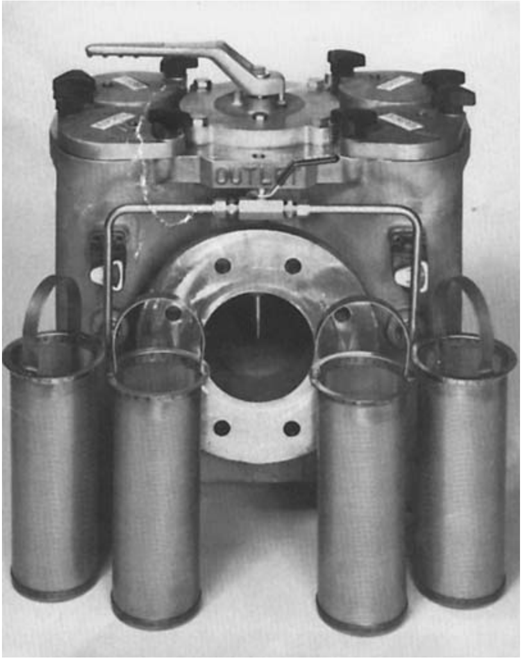
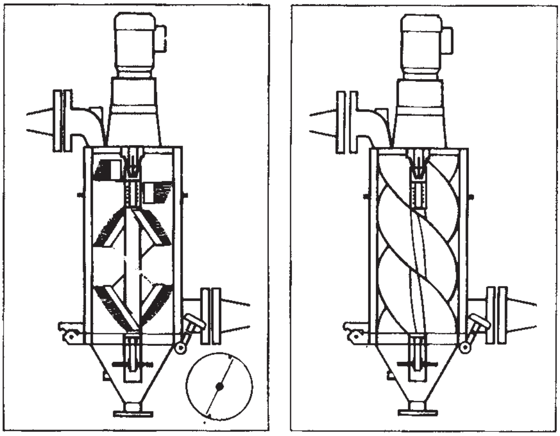


Figure 3.6 Multi-basket strainer



Brush model

Suitable for low viscosity products.
A special feature is the two bars in the perforated cylinder for cleaning the brushes.

Screw model

Suitable for heavy viscosity products such as animal fat and wax and to enable cleaning-in-place (CIP).

Figure 3.7 Self-cleaning strainers

3C. SCREENS

As the term is most commonly used in filtration technology, a screen serves two prime functions: as a large strainer, especially for water intakes and in wastewater treatment, and as a device for separating mixtures of solid particles into two or more sizes, either in the dry state or in liquid suspensions. In formal terms, the strainers described in the previous chapter are also screens (as is shown in Table 3.1), the main difference being size, although, as with any attempt to draw hard and fast lines in a classification, some overlap between 'strainers' and 'screens' is unavoidable. Strainers are essentially protective devices, against the presence of oversize particles in a flowing system, while screens have the equally important size classification function (although the protective role in, say, water intakes is obvious). It should be noted that there are plenty of applications in which screens act like a coarse filter, to separate solids from liquids (in particular, dewatering wet solids).

In the filtration spectrum, screens (and strainers) are characterized by having filter media made from perforated plates, woven wire or wedge wire bars, usually with fairly coarse apertures – although woven wire-based media are available down to 500 Mesh (25 μm), especially in test sieves. The material of the screen is usually metallic, although any form of metallic screen can be reproduced in plastic, with some loss of strength, but gain perhaps in material cost, and, in some applications, corrosion resistance.

Stationary water screens

A wide range of screens is used for the removal of solids from water in large-scale water handling systems. Where water is pumped from rivers or lakes (or from the sea, either as feed to a desalination plant, or for cooling purposes), screens are employed on the intake side to protect the pumps from debris in the water, although this does not necessarily eliminate the need for intake strainers or finer screens on the pump inlet itself. The selection problems of screening may also be specific to the locality involved, which can dictate the type of screen or protection necessary. Thus special protection may be needed to deal with weed or grass in sea water, which will easily pass through coarse screens or readily clog fine ones. In other localities, marine life inducted with the water may present a special clogging problem. These situations can demand highly individual solutions.

Screens are also used to remove large inorganic solids from sewage and industrial wastes. The principle involved is exactly the same. Solids are retained on the screening surface, from which they must be removed at regular intervals, to prevent clogging of the screen. This can be done by scraping or raking the screen, or employing moving screens.

A typical stationary screen consists of a vertical or near vertical grille of rectangular bars, with spacings of 25 mm or less. These can be cleaned by a rake, whose teeth engage with the spaces between the bars, and which moves upwards across the face of the grille, removing collected solids from it. This rake may extend the full width of the screen, and it is then lifted up to provide front cleaning by scraping the surface of the grille, and carrying solids up to the discharge point. Alternatively, and particularly for wider screens, the trash rake is much narrower than the width of the screen, and traverses that width, as well as being raised or lowered on a cable. The rake in this case is unguided, to allow it to ride over any large obstructions in the water. Rake teeth are hydraulically moved to their open and closed positions. All debris is picked up on the rake and then dumped over the top of the screen.

In a travelling screen, the screening surface consists of a number of hinge-connected panels or baskets, which hang vertically, supported by guides. The baskets are then elevated by a chain drive. Each screen in the array is thus progressively raised to the head end, carrying debris with it, where it is cleaned by a spray of water. The cleaned screens are then returned vertically to the bottom and brought forward to repeat the cycle of operation, working on an endless belt principle.

Developments in continuous self-cleaning screens have demonstrated considerable improvements in filtering debris from water, wastewater and even slurries.

The advantage of the back-raked screen is that the cleaning forks are positioned on the clean liquid side of the screen (Figure 3.8), and move through the screen from its back side, lifting the solids away from the screen and not forcing them into the gaps between the bars. The parked position for the cleaning rake is at the uppermost height of its travel. The cleaning mechanism is actuated from a water level signal (upstream level or differential) or by a timer. The cleaning rake is attached to a wheeled carriage that in turn is powered by a geared motor.

During the downward travel, the rake is in a retracted position. At the point of lowest travel, counter-balancing drives the rake into the bar spaces. If the rake does not engage due to heavy loading, the upward travel of the carriage forces the rake into position. The cleaning forks of the rake collect the solids from the screen bars and lift them to the discharge chute where a hinged wiper pushes the solids onto that chute.

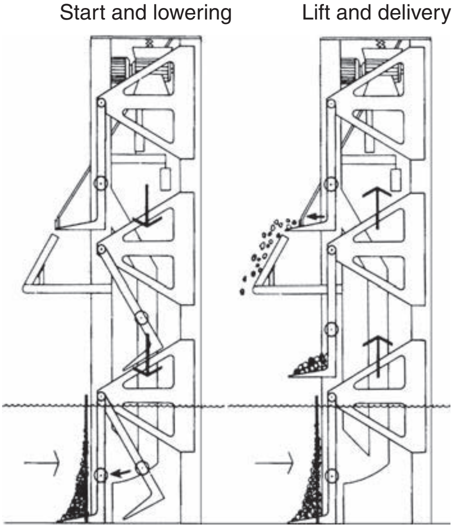


Figure 3.8 Back-raked screen

Intake screen systems

A different form of stationary water intake from surface water sources, such as submerged intakes for power, pulp and paper, or petrochemical industries, uses cylindrical screens at the inlet of the intake pipe, in single or multiple designs, as shown in Figure 3.9. These can usually be optimized to accommodate any set of conditions. In river systems, the screen cylinders are normally placed parallel to

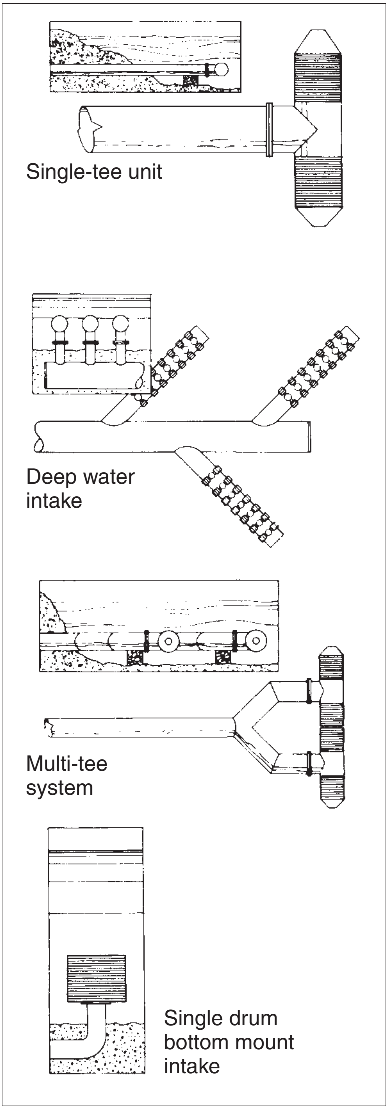


Figure 3.9 Submerged intake screen arrangements

the river flow to take advantage of that flow. In reservoirs or where severe seasonal changes in water depth are possible, an array of intake screens can be used to allow extraction from selected levels.

Biofouling can be a problem in marine intake systems, to which one solution is the use of copper-nickel materials to discourage potential encrusting life. On occasions it will be necessary to position screens where access is either difficult or limited, or in conditions where there is a high concentration of debris, so that cleaning of the screens is necessary if the system is to continue to function effectively. A normally used method is by air flushing, where a measured burst of air is released inside the screens, so as to force accumulated debris to break away from the screen, to be carried away by the ambient flow.

Rotating screens

All of the intake screens discussed so far have operated in a stationary mode (or at least stationary whilst screening). An important group of screens rotate, screening solids continuously through that part of the screen that is submerged, with accumulated solids carried on the surface of the screen out of the water, to a zone where they may be washed off the surface into some kind of sludge collector.

The disc screen is a large frame carrying two circles of wire mesh, sealed together at their circumference, and mounted on a substantial hollow shaft. The screen sits in a flow channel, with its shaft across that channel, and submerged to just above the shaft. Solids collected on the screen surface are carried out of the water by the rotation of the screen, with heavier solids lifted by suitable buckets. The emergent screen is then washed by a spray of water, transferring the solids into a receiving trough for disposal. Screens of this type may be from 2 to 4.5 m in diameter, and can be mounted in parallel for higher flow rates. Higher flows can also be achieved by mounting the disc with just one circle of mesh across the water flow. These screens are simple in design, and are mainly used for the removal of relatively fine solids from shallow water courses.

Rotating drum screens are made from a sheet of wire mesh, mounted on the outside of a cylindrical drum and rotating on a horizontal shaft. They have some kind of washing system to remove collected solids from the drum towards the top of its rotation. A simple arrangement has the drum situated across the water flow, which thus goes through the screen and out at the side of the drum. More complex forms of rotating drum screens include the micro-strainer, which has a flow from inside the drum, through the screen, and can trap solids down to a few micrometres, because of the cake of solids that collects inside the screen, before it is washed off at the top. A different form of rotating screen is exemplified by the Contra-shear and Roto-plug designs, which do not operate with a flooded screen but are sludge thickeners and drainers (Figure 3.10). The dilute suspension is fed inside the drum and the liquid drains quickly through the screen, while the separated solids fall to the bottom of the drum where they travel along the bottom, parallel to the drum axis, draining further as they do so, to leave by overflowing at the end of the drum. As these are sludge processing

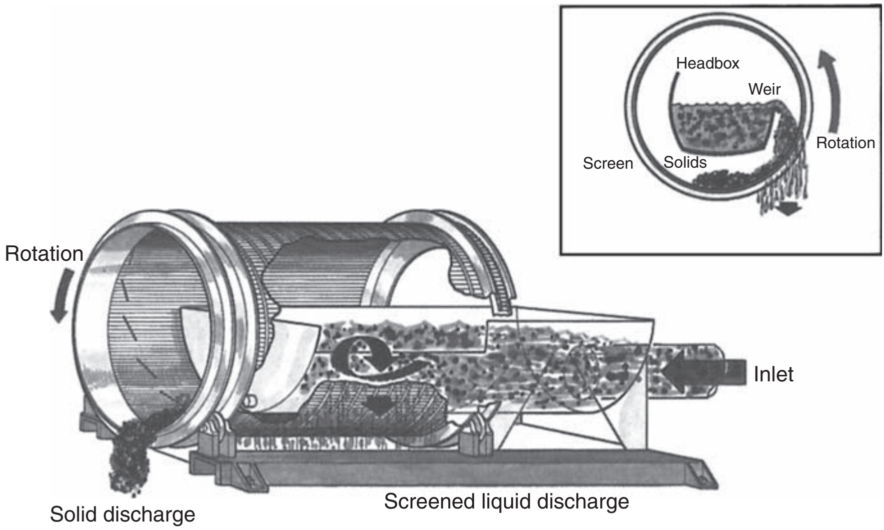


Figure 3.10 Contra-shear screen

screens, they find wide use in sewage treatment, pulp and paper processing, and fruit and vegetable pulp separations.

Well screens

Well screens are sleeve-like units fitted over the ends of intake pipes in water or oil wells. They well illustrate the nomenclature problem outlined at the start of this chapter in that they are relatively small and clearly act entirely by straining, yet they have always been called screens, and so are described here. In construction they may vary from simple slotted pipes, with or without a surrounding screen, to quite specialized designs of sleeves, as shown in Figure 3.11. They consist essentially of a cylindrical tube, sealed at one end, with porous material of some kind in that part of the walls that sit over perforations in the sides of the end of the suction pipe, over which the screen is fastened. They serve to prevent entry of particles of rock from the drill site into the water or oil being extracted.

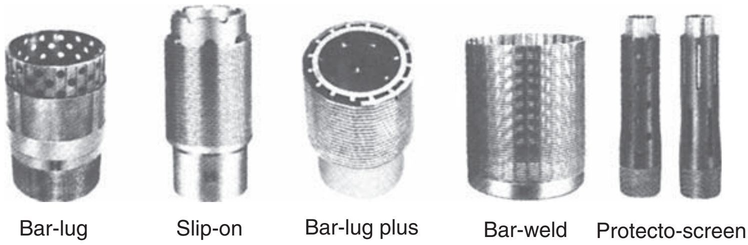


Figure 3.11 Types of well screen

The lug screen is basically a wire wrap screen located on vertical bars on a perforated pipe, facilitating free entry of fluid over the entire exposed surface of the screen, to increase its efficiency. This principle is further extended in the lug plus version, where the bars are welded to the wedge-wire screen, and the whole is shrink-fitted to the perforated pipe. The slip-on screen is of similar construction, but is a slip on fit. In the weld screen the wedge-wires are welded to vertical rods. The 'Protecto-Screen' incorporates a perforated protective shell guard over the wedge-wire screen.

PVC screens in sizes ranging from around 40 to 220 mm are gaining in popularity, particularly in shallow well applications. They have been shown to be more economical than metal screens, resisting corrosion from the salts and gases commonly found in fresh or salt water.

Size classification screens

The simplest form of size classification is the hand-held test sieve, fitted with a piece of precise wire mesh, and used to classify a sample of solids into two ranges of particle size – above and below the aperture of the mesh. These are used in the dry and shaken carefully and sufficiently to achieve the required size separation.

At the other extreme are the huge stationary screens (grizzlies), mounted horizontally or with a slight incline, and used in mineral processing, or coal or aggregate grading plants. These are made from sets of thick metal bars, usually fixed parallel to one another, onto which the solids to be sized will flow, either in the dry state or carried in a stream of liquid, usually water.

An important stationary, wet classifier, which can achieve a very sharp classification, is the sieve bend (originally known as the DSM screen). This, like many other screens, is made from wedge-wire bars, welded onto support bars, so that the wider flat face of each bar adjoins the corresponding faces of the bars on either side of it, with a small aperture left between the bars. If a structure like this were to be rolled up into a cylinder, with the wedge-wire bars parallel to the axis, and the controlled apertures on the inside of the curve, an excellent screen is formed (and is so used, for example, in the Contra-shear and well screens described above, and in centrifugal filters). The sieve bend takes an arc of this drum, usually less than a quarter of the circumference, and mounts it with the bars horizontal, and the upper part vertical. The screen accordingly bends away from the vertical the further down its structure. A slurry is caused to flow downwards on the inside of the top of the screen and thus tangential to it. As the slurry flows down, the liquid and the finer solids flow out through the apertures, and the oversize solids flow over the end of the screen.

There is no doubt that some kind of movement of the solids being separated, in a direction parallel to the screen surface, is beneficial to the screening process. This is partly so that a sharp contact with other particles will break up any loose agglomerates among the feed, and partly so that a specific undersize particle is given every chance to find an aperture through which it can pass. This motion is applied to screens by vibration (movement back and forth in one direction) and gyration (a two dimensional movement, basically circular).

Vibratory screens

A huge volume of solids is processed by means of vibratory screens. These can be either horizontal or gently inclined, and they incorporate the use of vibratory motors to achieve the required motion of the screen. In order to get flow of the separating solids across a horizontal screen, the vibrating motors need to run in different directions to each other so that when they are synchronized they will produce a straight line impetus, so that the solids will move across the screen and enable it to be used for screening, conveying and dewatering. When the screen is gently inclined the action of a simple vibration is normally sufficient to achieve the required flow of solids across the surface of the screen.

A vibrating screen may be firmly mounted on a vibration system below the screen, or it may be suspended by cables from the overhead vibration mechanism. These two are shown in Figure 3.12. Modern construction methods tend to use stainless steel screen elements and high-density plastic construction materials for the remainder, to give a reduction in mass, so enabling lower power motors to drive the system, making the operation much more energy efficient.

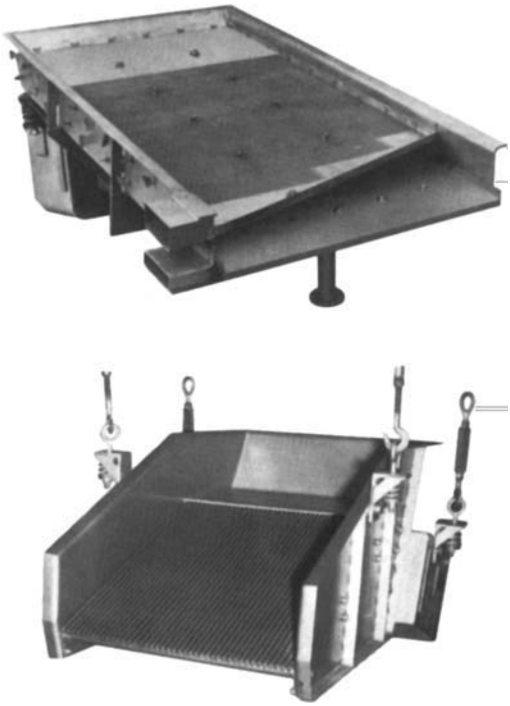


Figure 3.12 Vibratory screens

Gyratory separators

Gyratory screen separators, which impart a basically circular motion to the particles on the screen, are used for high capacity separation by size of dry materials, and for wet separations when oversize material constitutes a large percentage of the feed (a typical example is shown in Figure 3.13). Common practice with gyratory screens has been to adapt the motion of one type of machine to perform either wet or dry separations, since two distinctly different types of motion are required for the best efficiency.

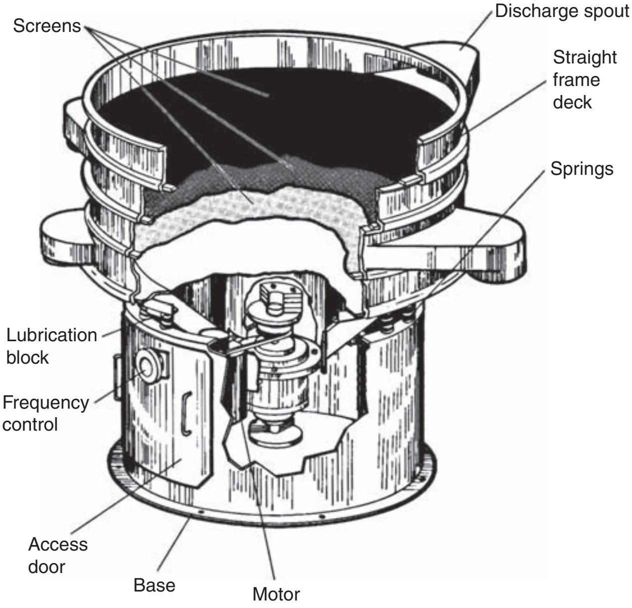


Figure 3.13 Gyratory screen

The separation of solids from liquids requires a crisp, long, horizontal motion to shear the feed stream and quickly pass the liquid through the screen. A minimum amount of vertical motion is used to convey solids out of the separator. Dry separation, on the other hand, normally requires precisely the opposite types of motion – minimum horizontal motion to spread the material over the screen in a controlled pattern, and a strong vertical motion to stratify the product so that particles can quickly pass through the screen openings.

The gyratory screen has become a remarkably useful processing tool, able to separate several solid fractions by the expedient of mounting a series of decks, one above the other on the one vibrating frame.

3D. NUTSCHE FILTERS

The next group of equipment types to be covered in this Section are all vacuum driven, and nearly all are intended for solids recovery, rather than for decontamination purposes. The simplest vacuum filter is the laboratory Büchner funnel, and the simplest practical embodiment of that is the Nutsche filter, which is found widely distributed throughout a range of industries, taking advantage of its simple, batch format.

The Nutsche filter is a vertical vessel, divided into two chambers by a horizontal perforated plate roughly at its mid-point. This plate may itself be the filter medium, or a sheet of finer medium may be laid onto the plate. In its simplest form, the upper chamber of the filter is an open feed chamber, into which the feed suspension is poured or pumped. The enclosed lower chamber is the filtrate receiver, to which the vacuum connection is made (at a level above that of the top of the batch of filtrate) to draw the filtrate through the filter medium, leaving the suspended solids from the feed as a cake on the upper surface of the filter medium. This cake will then be dug out of the filter, or lifted out on a removable filter medium, or tipped out by turning the whole filter unit through 180°.

Filtration in a Nutsche filter will probably start with some sedimentation of the fastest settling solids onto the filter medium, and then filtration under suction of the rest of the suspension. More complicated versions will include a vertically rotating shaft in the upper chamber carrying blades that will smooth out the forming cake or scrape out the formed cake. The upper chamber can be closed, so that the filter can then be operated under pressure rather than vacuum. The most complex form has the capacity to carry out a chemical reaction in the upper chamber, resulting in the precipitation of a solid product, followed by its washing free of reactants, and then sucking dry by the passage of air through the cake, before it is removed from the filter chamber.

The washing of a Nutsche filter cake must be done carefully to avoid the creation of channels through what is usually quite a thin cake, and also to avoid the mixing of filtrate and wash liquor if that is undesirable.

3E. TIPPING PAN AND TABLE FILTERS

The tipping (tilting) pan filter obviously, and the rotary table filter somewhat less obviously, are developments of the simple batch vacuum filter described in the previous chapter. The single tipping pan is a batch filter, just like the Nutsche, but other versions, including the table filter, are intended to allow more or less continuous operation.

Tipping pan and rotary filters are widely used in the mineral processing industries, and they are particularly suitable for handling rapid settling coarse crystalline solids, especially since settling aids the formation of filter cake. Very sharp separation of the mother and wash liquors is readily obtained, greatly facilitating wash liquor recirculation. By applying multi-counter current washing techniques, maximum extraction of solubles is possible, with minimum dilution.

The single tipping pan filter is a shallow rectangular pan, which is normally an open vessel, with a false bottom supporting the filter fabric. The filtrate chamber of the Nutsche filter is replaced here by a narrow space below the filter medium that is connected to the vacuum and filtrate discharge pipe, which links the pan to the filtrate receiver. This connecting joint allows the pan to be rotated through 180° (tipping) for the discharge of accumulated solids, after they have been adequately washed.

Feed is loaded into the pan and filtration takes place either by gravity or under vacuum, depending on the design of the unit and the filterability of the solids. Cake washing can be followed by air drying, if required, prior to removal of the cake by tipping the pan to empty out the solids. When the pans are in the inverted position, the filter fabric can then also be washed.

Tipping pan filters are also available as multi-pan units, with the pans arranged in a horizontal circle, like a wheel, with the spokes of the wheel represented by the filtrate pipe connecting each pan to a central vacuum pipe and filtrate receiver. The pans are now trapezoidally shaped to fit together in the annular filtration zone.

A set of pans within this annulus is used to carry out the filtration cycle of feed-filter-wash-discharge and the wheel rotates after each stage of the cycle so that each pan in turn is indexed into the appropriate station. According to the number of washing stages required, and the size of the pans, then up to four, or perhaps more, of these sets of pans may make up the complete circle.

The rotary table filter is an extension of the multi-pan filter design. The pans are replaced by segments of the annulus, which still rotates around in a circle so that each segment in turn filters and washes. The segments do not tip, however, to discharge the solid, which is instead scraped off the surface of the filter medium by a screw conveyor, over a flexible outer containing wall.

Feed to the rotary table is usually across a weir positioned over the full width of the segment. The filter medium is a single piece of material, in an annular shape, and the segments are divided underneath the medium, with appropriate filtrate discharge pipes. The action of the screw conveyor in removing the cake leaves a thin ‘heel’ of unremoved solids (or the medium would be rapidly abraded by the screw action). If this heel would be a problem, than compressed air is injected from below the medium, just under the feed point, to free the heel and mix it with the feed slurry.

Unlike the multi-pan filter, which can have several feed and discharge points, the rotary table filter moves continuously from one feed point to one discharge zone. Both are being supplanted in industrial usage by the horizontal belt filter.

3F. ROTARY DRUM FILTERS

The Nutsche, tipping pan and table filters are intended only for solids recovery from liquid suspensions. The rotary drum filter is mainly used for that purpose, but has some applications in clarification as well as solids recovery.

Rotary drum filters may be vacuum driven (rotary drum vacuum filters) or pressurized (pressure drum filters). The former are produced in a large variety of types and sizes, capable of meeting a very wide range of moderate and slow settling liquid-solid separation requirements in the process industries, foodstuffs production, mineral engineering, effluent treatment plant, and right down to laboratory sizes. Such filters have the advantages of continuous operation with high cake-washing efficiency and low specific power requirements. They can be used with a wide variety of filter cloths and with various discharge methods for filter cakes of differing consistencies.

The rotary pressure drum filter is a very much more complicated filter than the vacuum version, and so is more expensive and less widely used.

Rotary vacuum drum filters

A rotary vacuum drum filter consists of a cloth-covered compartmental drum suspended on an axial shaft over a feed trough containing the suspension, with approximately 50 to 80% of the screen area immersed in the suspension. The trough will usually include an agitator to maintain the feed suspension at a constant concentration.

The oscillating swing-type agitator, which consists of welded side arms and angle rake ploughs, is designed to prevent cake erosion from the drum surface but at the same time to maximize cake formation and production output. Other designs allow the agitator assembly to be removed from the tank with the drum still in place.

The drum is commonly divided into three sections known as the cake-building, de-watering and cake removal zones. The first two zones are under vacuum, whereby the water in the material being handled is sucked through the filter cloth, and the solid particles build up as a cake on the cloth. In the third zone the vacuum is released and compressed air jets may be used for cake removal. The compressed air can also be employed for clean-blowing the filter cloth.

A specific design of the rotary vacuum drum filter is shown in Figure 3.14. The drum rotates at 10 to 60 revolutions per hour and a vacuum of approximately 400 to 160 torr is built up with a liquid seal pump that is connected to the drum cells via the control head and filtrate pipes. This sucks the liquid through the filter cloth, and the solids contained in the suspension are deposited in a uniform layer on the cloth on that part of the drum that is submerged in the feed suspension.

The control head divides the filter drum into the different sections for filtration, washing, suction drying and cake discharge, so that in the course of one revolution each point of the drum area passes through these zones in succession. The filtrate runs off through the separator receiver and is discharged either by pumping or by utilization of atmospheric pressure (i.e. by use of a barometric leg). The filtered solid layer emerges from the suspension as the drum rotates, and following its emergence is washed, suction-dried and discharged from the filter cloth. The wash liquid is fed onto the cake either directly by means of wash devices such as weirs or spray nozzles, or of a wash belt lying on top of the cake.

The filtrate from the wash zone can be drained off separately from the mother filtrate. The filter cake is discharged by means of a discharge device of some kind, which covers the entire drum and which is specially suited to the cake thickness, consistency and structure (including scraper, roller, string, etc. – described below).

The filter cloth can be cleaned before it returns to the feed trough, either with water jets or with cleaning brushes. As the drum rotates, the cleaned filter is once more immersed in the suspension. If the filter cake is not washed, or if separation of the main and wash filtrate is not required, then the plant is equipped only with a filtrate separator. An arrangement of filter and ancillaries is shown in Figure 3.15 for the case where the cake is washed, but filtrate and wash liquors are not separated.

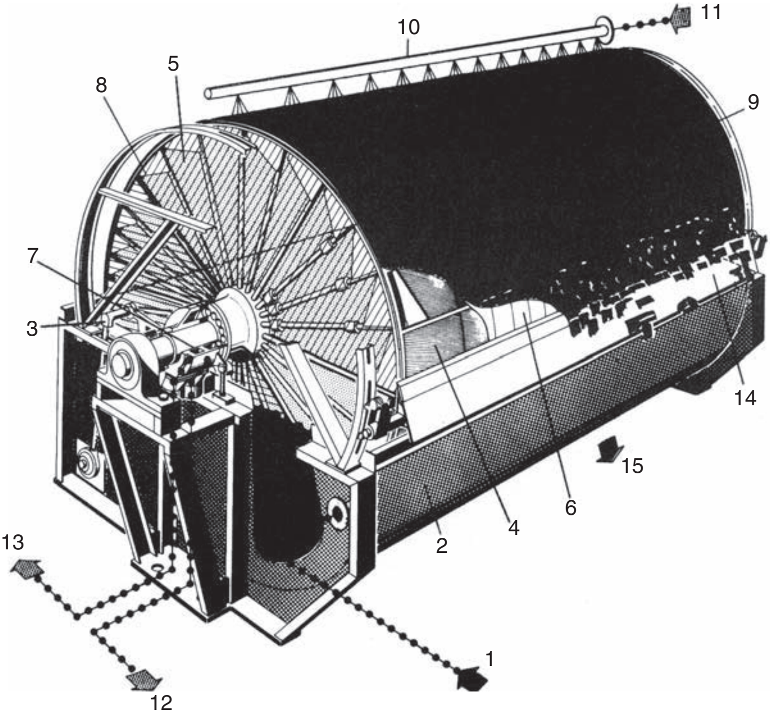


Figure 3.14 Rotary vacuum drum filter. 1, Suspension; 2, filter trough; 3, pendulum agitator; 4, filter cells; 5, drum; 6, filter cloth; 7, control head; 8, filtrate pipes; 9, filter cake; 10, washing device; 11, wash fluid; 12, mother filtrate; 13, wash filtrate; 14, discharge device (e.g. scraper discharge); 15, solid

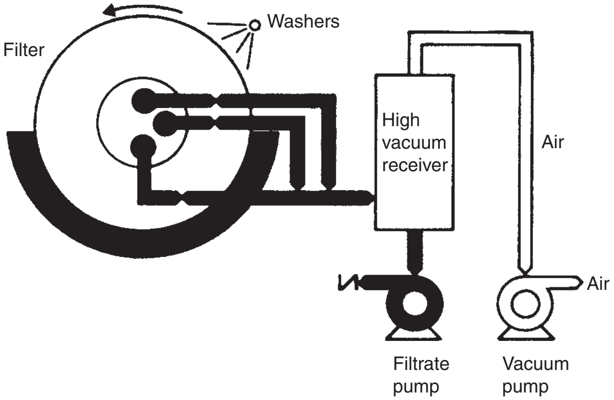


Figure 3.15 RVDF arrangement – no separation of filtrate and wash

(Instead of the filtrate pump, atmospheric pressure can be utilized for discharging the filter.) A filter system using a common vacuum source, but keeping the filtrate (strong liquor) and wash liquid (weak liquor) separate is shown in Figure 3.16.

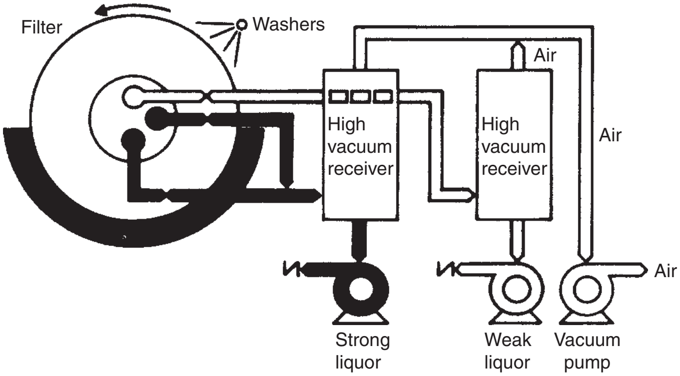


Figure 3.16 RVDF arrangement – filtrate and wash separated

The range of materials handled by rotary vacuum drum filters is shown in Table 3.3. For a long period the RVDF was the main process vacuum filter, a key processing tool in the various industries listed in Table 3.3, but its role has been taken to a considerable extent in recent years by the horizontal belt filter.

Table 3.3 Typical RVDF applications

Applications	Typical feed concentration % solids	Average filtering lb/ft^2/hr	Product moisture %	Vacuum cfm/sq ft	Discharge
Alumina trihydrate seed	35	175–235	10–13	7–10	Scraper
Apple juice	Low	(5 gph/ft^2)	–	4	Precoat
Barium carbonate	20–40	15–80	25–40	1–2	Scraper
Barium sulphate	50	55	30	4–5	Scraper
Calcium carbonate (ppt)	20	7–10	40–50	2-flap, 5 w/o	Scraper
Calcium carbonate (ground)	40–45	15–25	27	1–2	Scraper
Portland cement (DSM CCG)	65	145	18–20	1	Roll/scraper
Ceramic wastes	45	130	25–30	1–2	Scraper/roll
Coal (flot. conc.)	25	75–100	25	4–5	Scraper
Coal (refuse)	30	25–30	30	2–3	Scraper
Copper concentrate	50–60	33	6–10	1.5–3	Scraper
Corn syrup	Trace	(8–20 gph/ft^2)	–	4	Precoat

(*Continued*)

Table 3.3 (Continued)

Applications	Typical feed concentration % solids	Average filtering lb/ft^2/hr	Product moisture %	Vacuum cfm/sq ft	Discharge
Flue dust (blast furnace)	45	30	25–30	4	Scraper
Flue dust (oxygen converter)	25–30	20	30–35	1–2	Scraper
Flue dust (cupola)	25–30	10	30	2–3	Scraper
FGD sludge (lime system)	30	75–100	20–65	3	Scraper/belt
FGD sludge (limestone system)	30	175	15–45	2	Scraper
Gluten	10–20	2–5	55–65	2	Belt
Green liquor dregs	5–10	3.5	80	3	Scraper/belt
Green liquor dregs	5–10	4.5	50–60	4–5	Precoat
Iron oxide (pigment) (yellow)	10–25	4–10	55–60	2–3	Scraper
Iron oxide (pigment) (red)	13	3.5	30	1	Roll
Kaolin	16–26	10	–	1.5–2.0	Roll
Lithium carbonate	30	47	35–45	1	Scraper
Magnesium oxide (papermill recaust)	3	55	40	3–5	Scraper
Manganese tailings	10–14	4–7	45	1	Roll
Nickel carbonate	10	30	75	1	Scraper
H_3PO_4 (70%) polishing	Trace	8 gph/ft^2	–	4 max.	Precoat
Recaust, lime mud	25	0.7–1.5	25–35	10	Scraper
Silica gel	1–10	12.5	90	2–3	Scraper
Silver chloride	2	3	55	–	Scraper
Slop oil	Low	(2–4.5 gph/ft^2)	–	4	Precoat
Sodium bicarbonate (crude)	25–30	110–125	9	30	Scraper
Sodium nitrate	50–60	480	3½–4	67	Scraper
Starch (corn)	12–28	27–34	30–40	1.25	Belt
Starch (potato)	2–5	5	12–15	3.5	Belt
Sulphur (Stretford)	5	7.5–20	50	3	String/ scraper
Talc, white	43	60	44	1	Scraper
Talc, tan	28	14	40	1	Roll, scraper
Tin leach residue caustic	20	8.5	37	6–7	Scraper
Titanium dioxide	20	9–10	50	2–3	Roll, scraper
Uranium yellow cake	11–13	6	50	3	Scraper
Wine lees	Low	(2–20 gph/ft^2)	–	4	Precoat
Zinc carbonate	13–33	12–60	35–50	3.5	Scraper
Zinc leach residue	14	1.2	58	1.2	Scraper
Zirconium oxide	40	15–20	39	1	Scraper

Reverse filtration flow

The rotary vacuum drum filters described so far utilize a filtrate flow from outside the drum to the inside, where the vacuum is applied. Rotary drum filters also exist with filtrate flow from inside the drum. A simple version is little more than a rotating drum strainer, used to clarify raw water, as filters for the recovery of fibres in pulp and paper mills, and as polishers after final effluent treatment. The filter works on the hydrostatic pressure of the head of suspension, and there is no need for a vacuum pump. The filter medium is pleated so as to increase the total filtration area, and the drive is usually by means of a variable speed motor.

In operation the slurry is fed into the rotating drum through an outer feed box through the open end of the drum. The level inside the drum is controlled from the outer feet box. By maintaining a lower level on the outside of the drum than on the inside using an overflow device, the water is pressed through the filter medium. The first filtrate may contain some unretained fines that can be returned to the filter feed for reprocessing. The retained filter cake is held along the inside of the drum by baffles until it reaches the top position of the drum where it is then flushed away by an air blast into a discharge funnel.

A more important version, which does employ vacuum to drive the filtration, has the filter medium mounted around the inside of the drum, which is of open construction with annular walls that create a tank between them at the lowest part of the rotation. Vacuum is applied to the appropriate parts of the outside of the drum, creating a filter cake that is carried to the top of the drum's rotation, and is then air blown into a receiving chute. In this filter there is no problem of maintaining a constant concentration in the feed tank and so no need for an agitator.

Cake discharge methods

The choice of the most suitable method of cake discharge for a particular RVDF application depends not only on the nature of the cake, but also on considerations of protection of the main filter medium from wear. The cake can vary in consistency, thickness and structure according to the products being handled, from a paste-like substance to a consistent solid.

The *scraper discharge* (Figure 3.17) is widely used for effluent sludge, in mineral ore dressing or metallurgical working, for chemical process slurries, and similar products. The cake is carried about three-quarters of the way around the drum, to encounter a flat blade (doctor blade) usually stretching across the full width of the drum. The scraper blade itself may be fixed or self-adjusting. A fixed blade with high pressure blow-back at that point is more or less traditional in certain applications (such as coal slurry dewatering, metallurgical processing and so on). The blade is actually set at a small distance away from the surface of the drum, the actual separation of the cake being achieved by blow-back pressure, which lifts the medium briefly away from its supports, and the scraper thus merely guides the cake away from the drum.

A fixed blade may also be used without blow-back. In this case, the blade is set to skim a certain thickness of the cake, leaving the rest as a heel on the drum

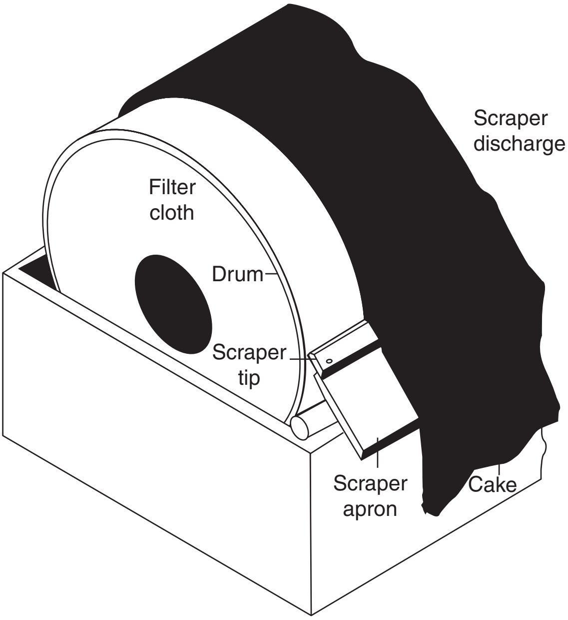


Figure 3.17 Scraper discharge

surface. This has the advantage of providing a drier discharged cake as well as subjecting the cloth to minimal wear. It is used particularly with crystalline solids and certain types of metallurgical sludges and for discharge from a precoat filter. In the latter case, the blade is set to remove all of the cake thickness plus a small thickness of precoat.

Self-adjusting scraper blades provide a better performance on thin filter cakes that crack readily. Here flexible plastic or spring-loaded blades are used, and the filter cloth is caulked, so that under a low pressure air blow-back it balloons outwards against the blades so that the blade and cloth remain in light, close contact. With a proper technique cloth wear is minimized in this way.

A scraper discharge belt filter is shown in Figure 3.18, which also features wash rolls in the 10 o'clock to 1 o'clock positions of the drum's rotation.

Roller discharge (Figure 3.19) is limited to cakes of an adhesive nature, which will transfer from the main filter cloth to a separate roller. The cake is then released from the roller by a scraper blade, which can be in close contact with the roller without causing cloth wear problems. In effect this is a form of scraper discharge, but eliminating any contact between the scraper blade and the cloth. The proper discharge of cake from a rotary drum vacuum filter is of paramount importance if this type of filter is to continue working efficiently.

The two previous methods of cake discharge have both been directly from the drum. The other methods involve the lifting of the cake off the drum and taking it

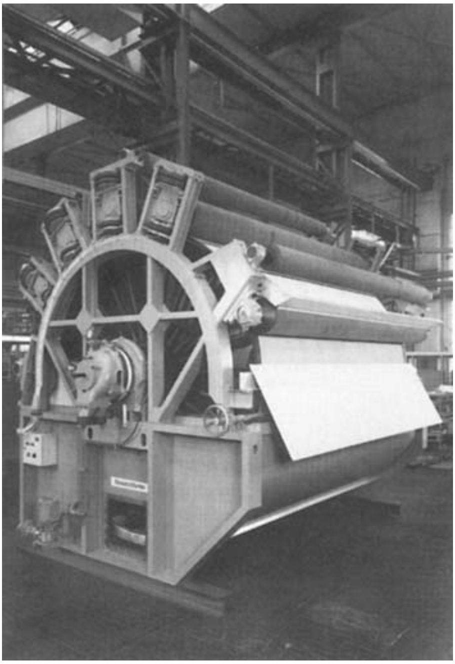


Figure 3.18 RVDF with full-width scraper

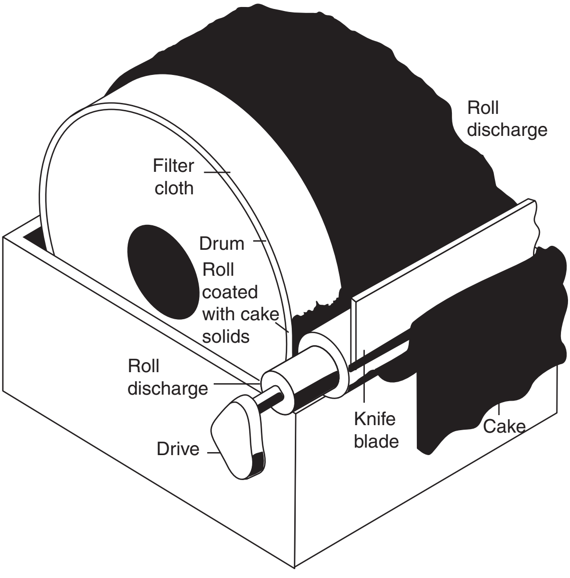


Figure 3.19 Roller discharge

to a separate roller at which it can more easily be released. A *string discharge* filter (Figure 3.20) has a number of endless strings, spaced at about 10–12 mm pitch over the width of the filter drum, the run of these strings being extended to form an open conveyor system passing over separate discharge and return rollers. Effectively, these strings lift the cake off the filter cloth at the point where they leave the drum tangentially, the cake then falls off the strings as they loop back around the discharge roll. A guide comb may also be incorporated between the discharge and return rolls, to retain string alignment and remove any residual cake adhering to the strings.

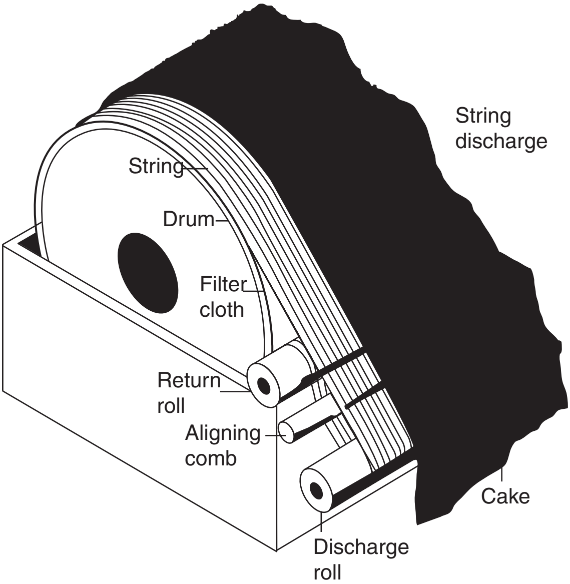


Figure 3.20 String discharge

String discharge minimizes mechanical wear on the filter cloth (enabling thinner cloths to be used), avoids the need for blow-back and provides continuous steady discharge at any suitable point away from the drum. The strings are normally made of synthetic fibres (e.g. nylon, polyester or polypropylene), chosen according to the product being handled. They can also be in the same material as the cloth, or in specific cases in the form of metal wire springs rather than individual strings.

Belt discharge (Figure 3.21) is similar to string discharge in operating principle, in that the cake is carried away from the drum to the discharge point, except that in this case the cloth itself is led off the drum over rollers of a smaller diameter to form a conveyor run, with the cake automatically tumbling off the cloth at the extremity of the run. The return run of the cloth then passes through a washing device, to clean it before it returns to the feed trough.

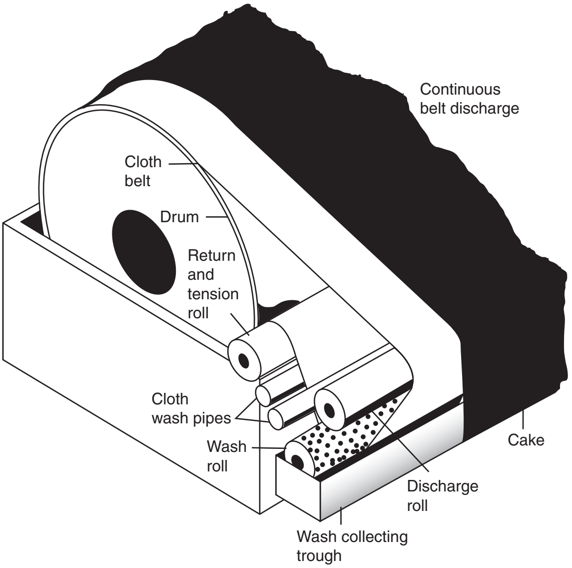


Figure 3.21 Belt discharge

This method provides complete support of the cake to the point of discharge and thus is capable of handling all types of cakes and cake thicknesses. It does not need blow-back and mechanical wear on the cloth is minimal. The washing on the return run also eliminates any tendency for the cloth to become clogged.

In the dewatering of flotation concentrate slurries, produced during mineral dressing operations, and in similar processes, the objectives are to recover the maximum amount of solids, produce saleable products where possible, and thus increase plant capacity at the most economic cost. There has been a significant improvement in process efficiency in this application by the use of belt discharge drum filters in place of disc vacuum filters and string/scraper drums.

The success of the belt-type drum filter is based on the simple premise that, if filter cakes can be removed completely and continuously from a vacuum filter, this must then give the best possible conditions for high capacity and good cake drying. To achieve this, the filter media must be kept in a clean condition and the discharge system must not rely on a high mechanical strength in the filter cakes. These requirements can be met completely by a belt discharge system. On this type of filter, the filter cake is positively supported on the filter medium, which acts as a conveyor carrying the cake from the filter drum to the discharge point. The filter medium, after removal of the filter cake, can be washed to maintain it in a clean state before it returns to the drum.

Belt discharge rotary drum filters can give throughputs of up to 30% higher than those previously given by rotary drum filters fitted with knives or string discharge. Even more dramatic improvements are being achieved as compared with the rotary disc filters previously used, where past experience has shown that this type are prone to poor discharge and filter cloth binding. Where this occurred, 50% or more of the cake often fell back into the feed trough, causing a decreased throughput. Appreciably lower moisture contents in the filter cakes are also obtained. This can give significant reductions in costs for subsequent drying and in some cases it allows the drier filter cake to be handled on conveyors, and blended with other material as a saleable product without difficulty.

Belt discharge filters also give much greater capability to deal with variations in the filter feed material and this is of particular importance when the filter is handling a natural material or effluent, in which appreciable variations can occur. Belt discharge filters are now widely used in coal washing and preparation plants, where units in operation are generally large, having areas of 55 to 75 m^2.

To ensure optimum performance of the filter, it is critical that the belts be trouble free in operation. It is important that the belt lies flat on the drum (it must not fold or crease) and the filter medium, in addition to having the right filtration characteristics, must also have the correct mechanical characteristics. The whole system (drum, discharge rolls, wash roll) must be constructed to a high degree of accuracy.

In general the life of the filter (i.e. the filter cloth) is in the range of six to twelve months, although cases of eighteen months are known. This contrasts with other types of vacuum filter where cloth life can be only three to four months. Key points to be considered in the design of belt discharge vacuum filters are:

1. accuracy in the fabrication of the filter drum
2. specially designed internal drain lines to minimize filtrate velocities, minimize wear and ease of maintenance
3. accurately manufactured discharge rolls mounted in self-aligning bearings with only one roll arranged for adjustment
4. simple and effective tracking system and belt tensioning system on one roll
5. heavy duty sloping collection trough for belt washings
6. availability of additional discharge roll for extra heavy duty
7. a facility to use an air knife not in contact with the belt to remove difficult cakes
8. availability of full width weir overflow on the filter trough to handle heavily frothed materials effectively and prevent spillage
9. standard fitting of wide range, heavy duty, variable speed, drum drive gearbox for maximum flexibility and service
10. availability of the manufacturer's total backup services at all stages of design, construction, commissioning and operation of the plant, to inshore optimum performance of the filter and the complete system.

Precoat filter

A range of filter media can be used on drum filters, depending on the specific application. Most media have a cut-off point below which value particles pass through the filter. One way to achieve high filtration efficiencies at low particle sizes is to coat the filter medium with a fine powder – the precoat – to build up a thin cake on which the main filtration can then be undertaken without loss. A precoat layer will be used for treatment of suspensions with a very low solid content and/or where very fine solid particles have to be filtered, and an absolutely clear filtrate is required. Diatomaceous earth (diatomite or kieselguhr) and expanded perlite, together with some grades of cellulose, are the more common precoat materials used for this purpose.

A rotary vacuum drum precoat filter is a specially designed version of the vacuum drum designed to use a thick layer of precoat material to clarify liquid flows. Initially a slurry of the precoat material is prepared and filtered to produce a cake of up to 100 mm thickness on the filter cloth. Then the feed trough is drained and refilled with the suspension to be filtered, which is now filtered in the normal way through the precoat layer. The filtered cake can be washed if necessary, and is then discharged by means of a full-width scraper blade. The blade removes the whole of the cake, together with a thin slice (about 0.5 mm) of the precoat layer.

This process continues until the precoat has been reduced to its minimum acceptable thickness, whereupon the process cycle is repeated. Drainage of filtrate is provided through grids and drainage mats, which allows for removal of filtrate from the entire compartment. The cake, of course, comes away with some precoat, and the process is only possible if this is acceptable – which it usually is, because it is mostly used for clarification. This process is distinctive on account of the high filtrate quality achieved.

Rotary pressure drum filter

The rotary pressure drum filter is basically a rotary drum filter enclosed in a large pressure shell, with suitable means for getting the feed suspension and any wash liquors in through this shell, and the filtrate and filter cake out of it. This results in a complex piece of machinery, as a glance at Figure 3.22 will show. In a rotary pressure filter the rotating drum carrying the filter cloth is contained within the sealed housing, which is divided into chambers, to which the various inlet streams are fed under pressure. The essential operations correspond to those of a vacuum drum filter, but filtration is under the higher driving force of a positive pressure and the cake and filtrate can remain fully enclosed. Cake discharge then takes place in a zone at atmospheric pressure, normally by a self-adjusting scraper.

The pressure differential necessary for filtration is achieved by means of gas pressure within the pressure vessel in which the filter drum rotates. The suspension is fed to the filter through a feed pipe. An operational filling level control device situated on either the feed pump or the feed valve ensures constant filling of the trough. An additional overflow pipe can be employed to ensure against overfilling.

Unlike the vacuum drum filter, the pressure differential necessary for cake formation is positioned and controlled between the filter pressure vessel and the filtrate separator. The filtrate from the cake formation and wash zone, and gas from the cake drying zone, flow over the control head and into the separator via the filter

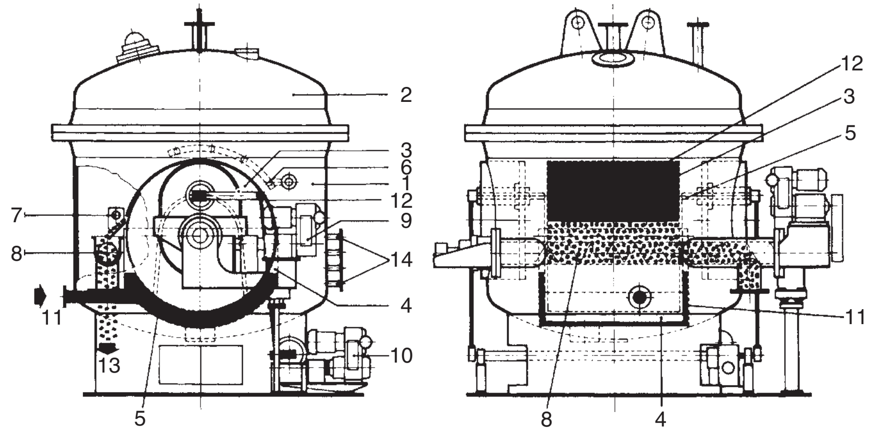


Figure 3.22 Rotary pressure drum filter. 1, Pressure vessel; 2, cover; 3, filter drum; 4, filter trough; 5, pendulum agitator; 6, wash unit; 7, scraper; 8, screw discharge; 9, drum drive; 10, agitator drive; 11, suspension; 12, filter cake; 13, solids; 14, filtrate

cloth covering, cell inserts and filtrate pipes, as in the vacuum drum filter. The filtered cake can be washed in a similar way and the separated filtrate can also be discharged at this stage.

The filter cake can be separated from the drum by means of the various discharge methods described previously for vacuum drum filters. Doctor blade and roller removal are preferred for reasons of construction space. The solid is removed from the volute in the surge chamber and transported to the laterally positioned discharge chute. Depending on the mode of operation and the consistency of the filter cake a pump, pressure lock or valve is employed for the final discharge of the solids from the pressure vessel.

Pressure drum filters are suitable for processing at high pressures and/or high temperatures. They are particularly suited for foodstuffs production, antibiotics, dyestuffs, agricultural chemistry, solvent refined coal products, waxes, oils and grease, paraffin and all high-viscosity solvents at normal temperature. They are particularly suited to applications where the liquid is easily vaporized and to filtration processes in protective gas atmospheres.

3G. ROTARY DISC FILTERS

Rotary disc vacuum filters have the advantage, compared with rotary drum filters, of giving a much larger filter area per unit of floor area. They are thus particularly suitable for the processing of bulk products, for example in coal preparation, ore dressing, pulp and paper processing, and so on.

The principle of construction of a rotary disc vacuum filter is that a number of filter discs are mounted, parallel to one another, on a horizontal shaft. Each disc is made of interchangeable sectors covered with the filter medium, which can be taken out for fitting and removing filter cloths. Conventional disc filters rotate the discs through a sump into which the suspension is fed. The sump will usually have an agitator to maintain constant suspension concentration, and therefore even cake formation. Vacuum is applied to the disc's sectors through pipes in the core of the central shaft, along which the filtrate is also removed (Figure 3.23).

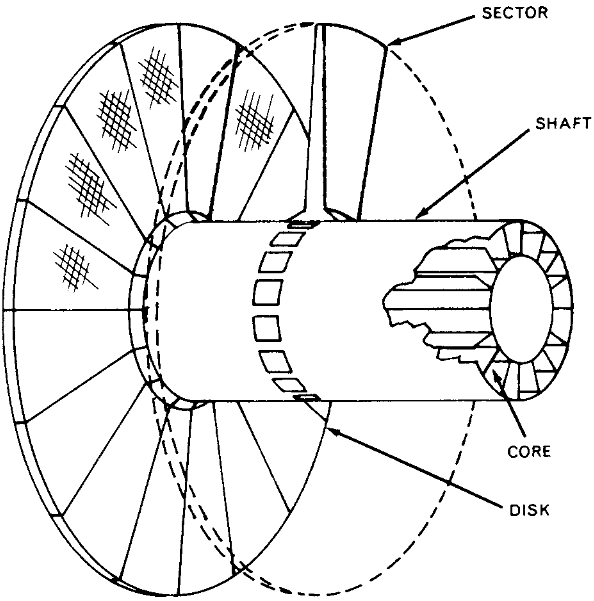


Figure 3.23 Elements of rotary disc filter.

Cake collects on the submerged parts of each sector, and is removed from the suspension as the disc rotates. The cake is then treated as necessary, for example by washing, and is removed by washing or with a scraper just before re-entering the trough. In other designs, each disc rotates in its own narrow trough, effectively sub-dividing the filter into a number of individual cells. In this case agitation in the trough is not necessary, and the wetted area of disc can be greater (typically 50% as opposed to 35 to 40% with an open trough). Also it is possible to isolate sets of troughs from one another so that two or more different products can be handled simultaneously by the same filter.

The filter area, and thus filtering capacity, of a rotary disc filter can be increased by increasing the number of discs in the complete unit. Standard units available may have from one to twelve or more discs, and tend to be made of plastic material. Each disc in turn may have up to 30 filter cells depending on the filter's diameter. Drainage tubes are large and mounted outside the shaft.

A development of the rotary vacuum disc filter is equipped with a central discharge of the separated cake from the filter (Figure 3.24). The discs are now mounted on the outside of an open rotor, inside which is a stationary trough, with a screw conveyor at the bottom of it. As the sectors pass through the feed trough, they accumulate cake in the normal way, but then this is blown off the discs at the top of their rotation, to fall through the openings in the rotor. This is an efficient design of filter, with greater effective submergence of the discs. This type of filter is not limited by maximum inlet consistencies: as long as the stock is fluidized then it can be processed by the unit. This allows applications not normally susceptible to vacuum disc filtration to be routinely handled.

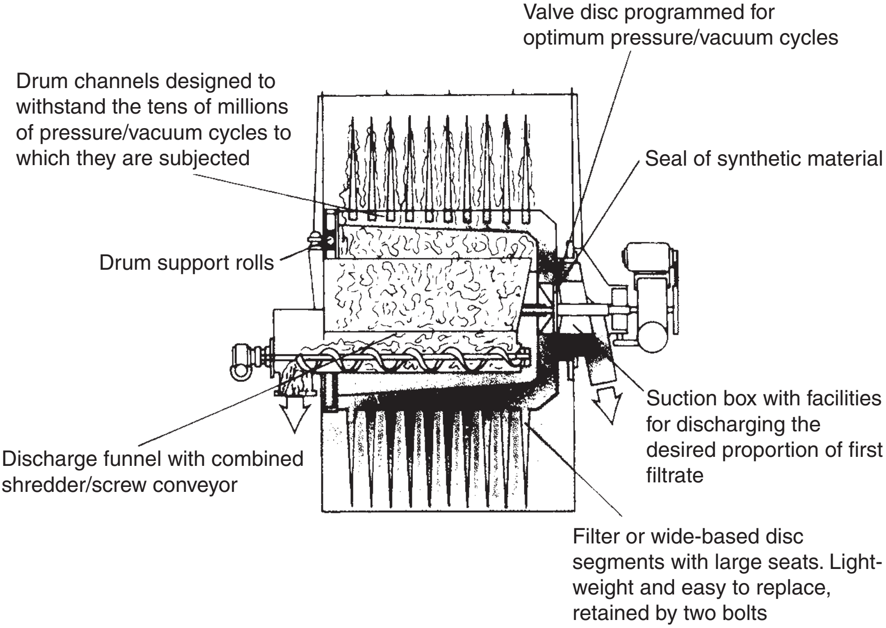


Figure 3.24 Multi-disc filter with central discharge

Capillary disc filter

The capillary disc filter looks like any other standard rotary vacuum disc filter, as can be seen in Figure 3.25, but the filter medium is a finely porous ceramic disc, which draws filtrate through the disc material by capillary action, under the applied vacuum. The filter discs are made of sintered alumina with uniform micropores less than 1 μm in size, which allows only liquid to flow through it. Despite an almost absolute vacuum, no air penetrates the filter material. The disc material is inert,

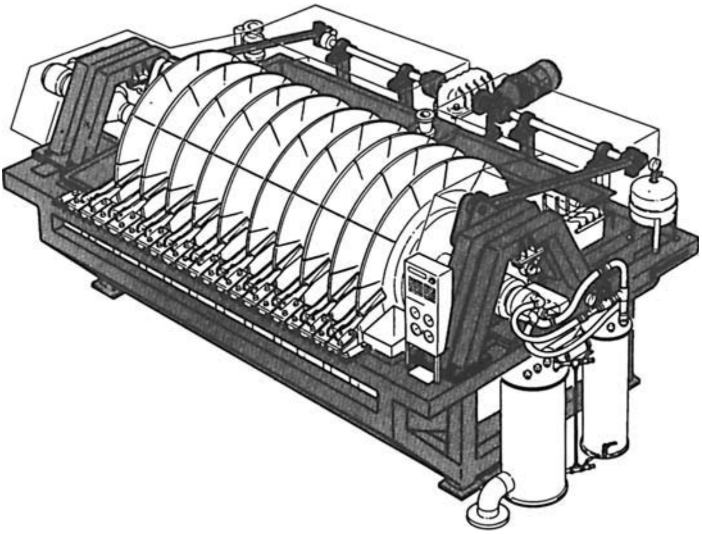


Figure 3.25 Capillary disc filter

resistant to almost all chemicals and slurry temperatures, making the system very versatile for the chemical, mineral, metallurgical and waste processing industries.

Cake formation takes place on the discs as they rotate through the slurry. A vacuum pump creates a very high vacuum level, which draws liquid through the discs into the filtrate lines. Solids built up rapidly on the external surfaces of the disc and the microporous structure prevents any solids from penetrating the disc surface. As the discs rotate, capillary action continues uninterrupted across the disc surface until all free liquid is removed from the solids. The accumulated cake is exceptionally dry, and is removed from the disc surface by a set of scrapers, leaving a thin heel on the surface to protect the disc from mechanical abrasion.

Some filtrate is used to back-flush the discs. This removes residual cake and cleans the microporous structure of the discs. The discs will eventually become clogged, and the ceramic plates can be regenerated, and full permeability restored, by ultrasonic cleaning on a regular or periodic basis, alone or in combination with chemical cleaning.

Although disc-type vacuum filters are not normally well suited for cake washing (because the wash water runs too quickly off the surface of the cake), the capillary action filter has proved the exception. Wash liquid is sprayed on the cake solids, to remove additional filtrate or impurities. This displacement washing is not susceptible to the difficulties of conventional filtration systems, where cake cracking, channelling or uneven distribution occurs.

Capillary filtration can provide for a high product output capacity with the produced filter cake having a very low water content. Disc filters of this type are considered to be energy efficient, using up to 90% less energy than other vacuum filters, because no air passes through the plates.

3H. HORIZONTAL BELT FILTERS

Horizontal belt filters working on the vacuum principle were originally developed for process applications where intensive washing is required, but are now also employed for a wide variety of filtering requirements. They have become such a versatile processing tool that they have taken a considerable share of the market from the former workhorse of the vacuum filter business, the rotary drum filter, and also quite a share from traditional filter press applications.

Apart from the simple paper band filter, the horizontal belt filters are continuously operating filters, used for the recovery of solids from suspensions containing quite high concentrations of solids. These generally fall into three categories.

reciprocating vacuum trays
rubber belts and a stationary vacuum system, and
with a supplementary press belt device.

Band filters

Unlike the other horizontal belt filters, the (paper) band filter is a device used for clarifying machine tool and similar coolants and lubricants free of contaminants. It began as a means for holding a sheet of paper through which the oil/water emulsions could flow, and has developed into quite a sophisticated continuous filter.

An automatic band filter consists of an endless honeycomb wire mesh belt that carries the filter fabric through a trough containing the liquid to be filtered. Originally using paper, such filters now increasingly use nonwoven filter fabrics. The liquid to be cleaned enters through an inlet onto the filter medium, which is held in a pool of the liquid by the endless belt (Figure 3.26). The contaminated liquid is cleaned by passage through the filter medium. As filtered solids build up, the permeability of the fabric decreases, causing the liquid level in the pool to rise

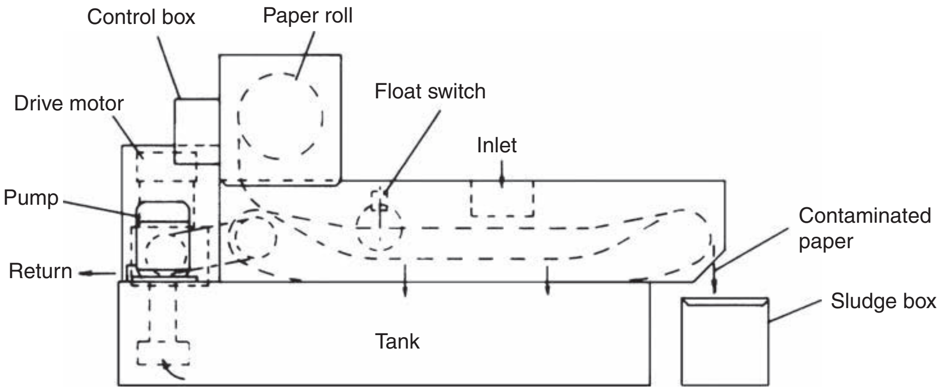


Figure 3.26 Band filter

until a float switch is triggered. This causes the filter belt to move forward automatically, carrying the dirty filter fabric out of the pool so that it can be dumped into a sludge collection box. The same movement unwinds fresh medium from a feed roll and moves it into the pool, automatically matched to the flow rate of the contaminated fluid and the build-up of solids.

Many filters of this type are capable of providing adequate decontamination of the feed liquid just using the hydrostatic head in the pool, i.e. it is a gravity filter. More complex versions, with more demanding clarifying needs, use media with higher resistances, and vacuum is then used to drive the filter.

This type of filter has found particular application for the continuous cleaning of coolants and other liquids and emulsions, especially where there is a need to separate particles from liquids similar in viscosity to water, such as machine tool lubricants, cold rolling mill coolants, and some water treatment or effluent control duties. Flow rates generally run from 20 to 6000 l/min, and if higher flow rates are required, then units can be connected in parallel.

In a large engineering works where there are many machine tools, then a central band filter system will normally be installed to serve all of the work stations. This type of system typically supplies cleaned coolant to transfer lines, special machines and machining centres.

Where clean liquids are constantly required and abraded particles are produced, varying in size, shape and material, an automatic band filter with a nonwoven filter fabric will as a rule provide a cost-effective solution.

Florentine filter

In the production of edible oils from oil seeds and oil-rich fruits it is necessary to process the crude oil to separate pure oil (olein) from the crystalline solids (stearin), the amount of each depending on the temperature of the process. The growing importance of palm oil processing meant that the traditional rotary vacuum filter was not sufficiently effective in this separation, and the Florentine filter was developed to enable higher processing rates in a continuous flow. This ‘dry’ fractionation step is used in the treatment of a wide range of oils and fats, from 2°C (hardened soybean oil) up to 45°C (tallow).

The Florentine filter has a stainless steel belt, which acts as the sole filtering medium (as shown in Figure 3.27). The belt is stretched between two driving drums and passes over the horizontal opening of a tank held under vacuum. The design of the belt is such that olein will drain through it even when the viscosity is high. The top of the filtration zone is air conditioned to a temperature just above that of the crystallized oil, so as to prevent the crystals from melting or an increase of viscosity. To eliminate any particles that may be driven through the first section of the belt a recycling tank collects the first filtered olein, which is then pumped back to the feed line. Filtration takes place beyond the recycling tank over what can be termed a continuous precoat.

This is a special type of filtration system that can separate large amounts of solids, as high as 60 or 70%. However it is only usually supplied as part of a specific filtration

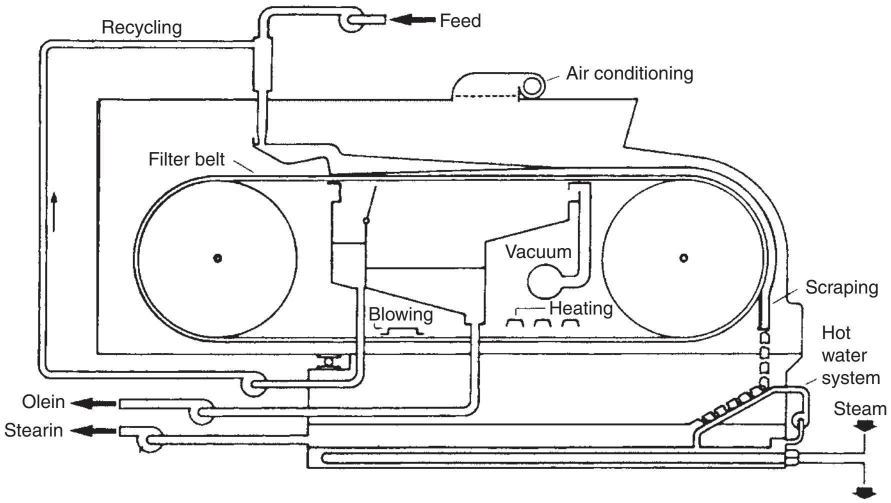


Figure 3.27 Florentine filter

process, where crystallization of the mother liquid is very important. The development of the diaphragm filter press has taken some of the dry fractionation business from this type of vacuum filter.

Vacuum belt filters

The vacuum belt filter employs a continuously moving horizontal belt of filter medium, commonly of woven wire mesh, moving between two rollers. In the forward direction, a suspension, of medium to high solids concentration, is fed onto the upper surface of the belt close to one roller. The cake formed in the feed zone is carried through dewatering, washing and drying zones, before being discharged as the belt turns round the other roller. The belt returns to the first roller through a cleaning device of some kind. The vacuum is applied below the filter medium to suck the filtrate through cake and medium, the filtrate leaving the filter through the vacuum connection, to be caught in the filtrate receiver. The main difference among types of vacuum belt filters lies in the way in which the vacuum is applied.

Reciprocating tray machines have vacuum trays that are individually evacuated and clamped by suction onto the underside of the belt. The trays move forward with the belt filter medium at the same speed, acting as a support for it. At the end of each stroke, with filtration and washing completed, the vacuum in the tray is released and the belt continues to move at a constant velocity. The tray is retracted downwards, away from the belt, to return to the start position, to be evacuated and for the process to be repeated. As the trays move with the belts, there are no sealing problems between belt and vacuum space, and so no air in-leakage, and there are no problems of friction, and consequent wear between belt and vacuum box. A typical tray filter is shown in Figure 3.28. This type of belt filter can be constructed from stainless steel or plastics.

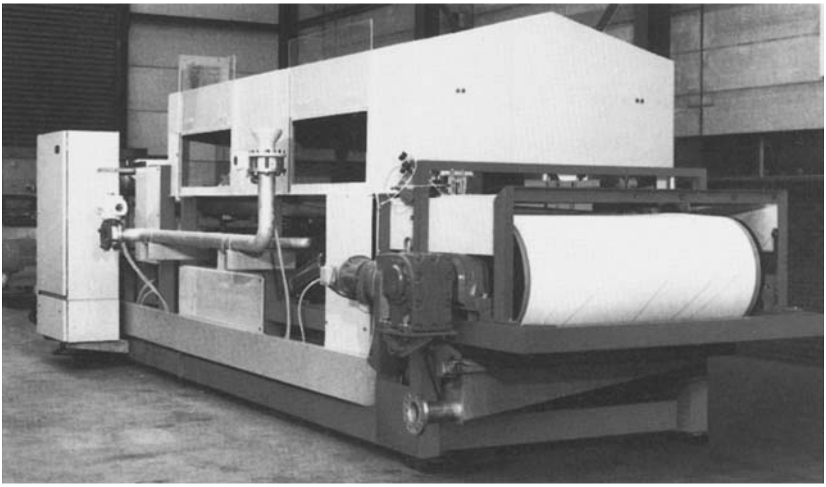


Figure 3.28 Reciprocating tray filter

The *rubber belt* filter has a continuous thick rubber belt running underneath the filter medium, to act as support for the medium. This extra belt, which has its own rollers, is grooved and perforated so as to allow the vacuum to reach the filter belt, and also to accept the drained liquid and pass it to stationary vacuum boxes or trays underneath. As with any horizontal belt filter, the length can be extended to incorporate zones for thorough washing as well as for filtration and dewatering. Reciprocating tray machines are usually lower in cost than rubber belt machines, which tend to provide a higher cloth speed and carry a heavier cake load.

Some solids are difficult to dewater, or at least to dewater sufficiently for the next step in the process, and the required degree of dewatering is achieved by the use of a *press belt*, which applies a squeezing of the solids to supplement the vacuum. The press belt may be external to the filter, in which case it takes the form of a short stretch of belt pressed down against the top of the filter cake. The press belt itself is separate from the filter belts, and is supported on, and driven by, a set of rollers above the main level of the filter.

The press belt feature may, alternatively, be integrated into the main belt filter, by taking the filter belt and cake into a section of additional rollers that compress the press belt on top of the cake. This is then effectively a belt press, as described in Section 3P.

Gas-tight vacuum belt filters are a valuable development in belt filtration technology. They are required where the solid materials or liquids involved in the process give off fumes, which may be toxic or chemically explosive and/or just create an unpleasant atmosphere or have to be processed in an inert atmosphere. Designs are now available that can provide a nitrogen purged atmosphere as overpressure. A high proportion of gas-tight machines are built for use with alcohols, but a wide range of chemicals including acetone, hexane, methylene chloride, and acetic acid at 90°C have been successfully applied.

3I. CENTRIFUGAL FILTERS

Centrifugal separations are of two broad kinds, those using filtration and those operating by sedimentation. The latter are covered in Section 7, while centrifugal filters are the subject of this part of Section 3. Also broadly classifiable into two types, centrifugal filters, which are essentially devices for recovering solids from liquid suspensions, are defined by the way in which solids move within, and are then discharged from, the centrifuge.

All filtering centrifuges consist of a rotating basket, cylindrical or conical in shape, out of the open end of which the separated solids are discharged. The basket is supported at the other end on the drive shaft, coming from a fixed or variable speed motor. The walls of the basket are made from a porous filter medium, usually woven wire mesh, perforated plate or welded wedge-wire screen, with filtrate passing through the basket from the inside out into a surrounding casing, leaving the solids behind as a cake on the filter medium.

The *fixed bed* filtering centrifuge, as its name implies, lays the separated solids down as a cake that stays in place on the walls of a cylindrical basket during the filtration, washing and dewatering stages of the cycle. The centrifugal force, which varies with the rotational speed of the basket, enables very effective cake formation and processing. Once the cake is dewatered, it is removed from the basket manually, semi-automatically or completely automatically. The removal of the cake may need the machine to be stopped or slowed down, although some automatic machines can discharge at full bowl speed. The fixed cake centrifugal filters are therefore batch machines, although some of the completely automatic centrifuges have a very short cycle and can appear to be almost fully continuous in operation.

In the *moving bed* centrifuge the solid particles quickly separate from suspension in the feed zone, and, once at the wall of the basket, move along the basket in a direction effectively parallel to that of the axis of rotation, until they reach the open end of the basket, from which they are discharged into a collecting ring around the outside of the basket. Filtration, washing and dewatering all take place as the cake moves through the basket, each stage taking a relatively short time because of the high centrifugal force. Baffles in the casing around the basket enable filtrate to be kept separate from wash liquors. Movement of the cake is caused by mechanical devices in a cylindrical basket machine, or by the component of the centrifugal force in the axial direction for conical basket centrifuges. This movement may create continuous cake flow, and hence a continuously discharging centrifuge, or very short cycle semi-continuous movement that is almost continuous.

Most centrifugal filters are quite complex machines, with that complexity very much a consequence of the need to be able to handle, and especially discharge, the separated solids, as near continuously as possible, while causing the minimum of damage to the solid particles, especially where these are crystals.

Fixed bed centrifuges

The fixed bed centrifugal filter is thus a batch-operated device for recovering solids from liquid suspension. All types have cylindrical baskets, open to the atmosphere (or to the enclosing casing) at one end. Filtrate passes through the filter medium and the developing cake, into the casing and so to a filtrate receiver. The formed cake must then be removed at the end of the batch, this removal being the main design feature of the centrifugal filter.

The basket is mounted on a drive shaft, which may be directly coupled to the drive motor, or the motor may sit to one side of the centrifuge, with a pulley and belt connection to the drive shaft. The axis of the basket may be vertical, with the open end at the top (the reverse orientation, with open end at the bottom is perfectly feasible, but rarely seen), and with suspension feed through the open end. Cake removal can be through this open end, or through openings in the base, provided that the drive mechanism is properly enclosed.

The basket orientation can also be horizontal, which is the preferred case for the more complicated semi-automatic and automatic discharge versions. An inclined orientation is also possible, although less common.

One of the problems of centrifuge operation is the uneven laying down of the cake, which can cause out-of-balance forces in the rotation, with consequent vibration. The most common way of dealing with this problem is by supporting the basket at three points around its circumference. Such an arrangement with a three-column suspension is shown in Figure 3.29 (which also shows a number of internal items, for cake washing and discharge). An alternative to this support from beneath is the use of a top driven shaft from which the basket hangs – the pendulum centrifuge.

A three-column basket centrifuge can be equipped to handle various filling, washing and discharge requirements in a discontinuous filtration process, with minimum attrition of the solids. The suspension to be separated enters the machine through a stationary feed pipe or over a rotating feed cone at the bottom of the basket. The feed cone is designed to effect a very gentle acceleration of the suspension up to basket speed. When the basket is full of solids, the feed valve is closed off, frequently by automatic control. The subsequent process consists of drainage of the mother liquor, washing of the solids, drainage of the wash liquid and finally discharge of the cake.

The simplest way in which discharge can be effected is to stop the rotation of the basket and then to dig out the accumulated cake by hand, through the open top of the basket, a situation illustrated in Figure 3.30. Slightly more complex is to use a

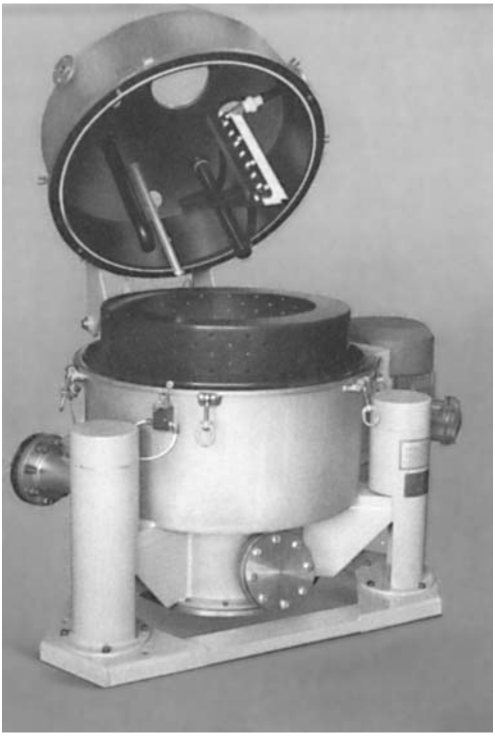


Figure 3.29 Three-column basket centrifuge

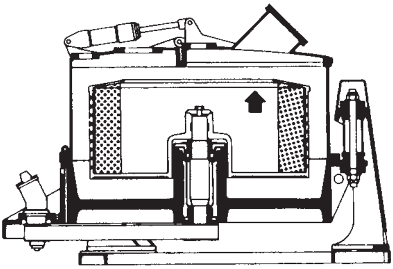


Figure 3.30 Manual discharge

cloth bag or an inner basket, and to lift this out, with all of the cake, as shown in Figure 3.31. Bag removal ensures that no solids are left behind. For both of these methods, the centrifuge must first be brought to rest.

A further increase in complexity involves the use of a paring knife mounted on the top of the centrifuge casing, which slices the cake off the inside of the basket, as shown in Figure 3.32. The cake solids then fall through openings in the base of the basket, to be collected below the centrifuge. If the nature of the accumulated cake is

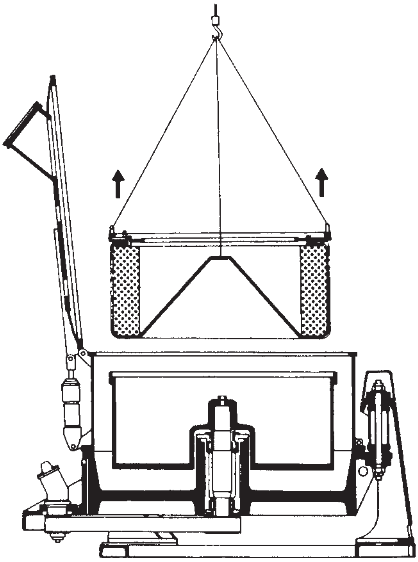


Figure 3.31 Bag or liner discharge

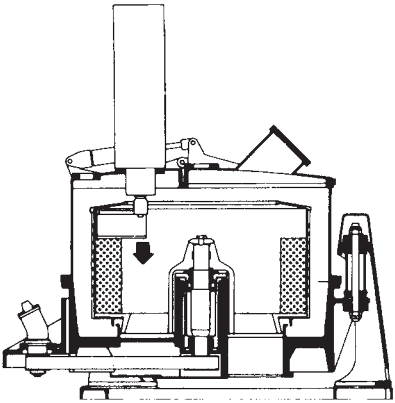


Figure 3.32 Scraper discharge

suitable, then the knife may be replaced by the tip of a vacuum pipe, which sucks the cake away from the basket, to be carried up and away by a pneumatic transport system, as in Figure 3.33. In either of these cases, the centrifuge is still rotating as the solids are removed, possible at full speed, but the paring knife or suction pipe cannot be allowed to touch the filter medium, for fear of wearing it away. As a result, a heel of unremoved cake solids is left on the filter medium. This is not a problem if the next batch has the same composition as the first, but if the solids differ, then the heel has to be washed or dissolved away before the next batch can be filtered.

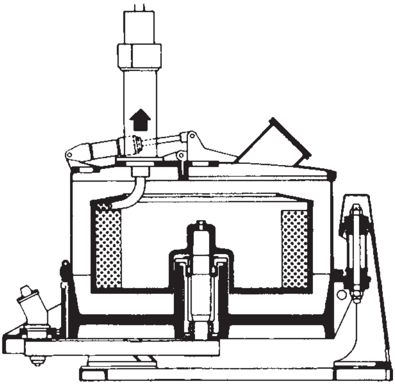


Figure 3.33 Pneumatic discharge

A major application for the perforate basket centrifuge of this type is in the separation of sugar crystals from the mother liquor after crystallization. Indeed, they are then called sugar centrifugals.

As can be seen from the drawings of Figures 3.30 to 3.33, the vertical basket centrifuge can be fitted with a lid. Whilst this may be to give containment against splashes, it can also be made gas-tight, so the centrifuges can be used for hot or toxic suspensions, or to contain organic vapours.

The major group of centrifugal filters with horizontal axes of rotation all have a scraper blade or knife, which cuts into the dewatered cake in a peeling action, so that the slices of cake fall into a duct that carries the solids out of the open end of the basket. The peeling knife may extend the full width of the cake, or it can reciprocate across the cake at the same time as cutting into it. A typical *peeler centrifuge* can be seen in Figure 3.34, showing a full-width peeler knife, and a solids discharge duct fitted with a screw conveyor.

The peeler centrifuge of Figure 3.34 can also be sealed against vapour loss, or given a nitrogen blanket to protect the cake (or filtrate) from air oxidation.

As with the basket centrifuge, the peeler centrifuge operates in the full filtration cycle of filling, draining, washing, dehydrating and finally peeling. This adjustable batch cycle is in most cases controlled automatically. The various operations within a batch can be performed at constant or varying speed of the centrifuge basket, it being quite normal to reduce the rotational speed during the peeling process.

In operation, the suspension is fed into the rotating basket through a feed valve. The feed step is interrupted by a feed controller as necessary, and feeding is repeated until the basket is filled. Filtration begins during the feed process and is completed when the level of the mother liquor submerges under the cake surface. A wash valve, controlled by a timer or flow meter, directs the wash liquid onto the cake through a wash pipe provided with spray nozzles. A conically shaped housing allows for the separation of the mother liquor from the wash filtrate, which is a particular advantage for multi-stage washing.

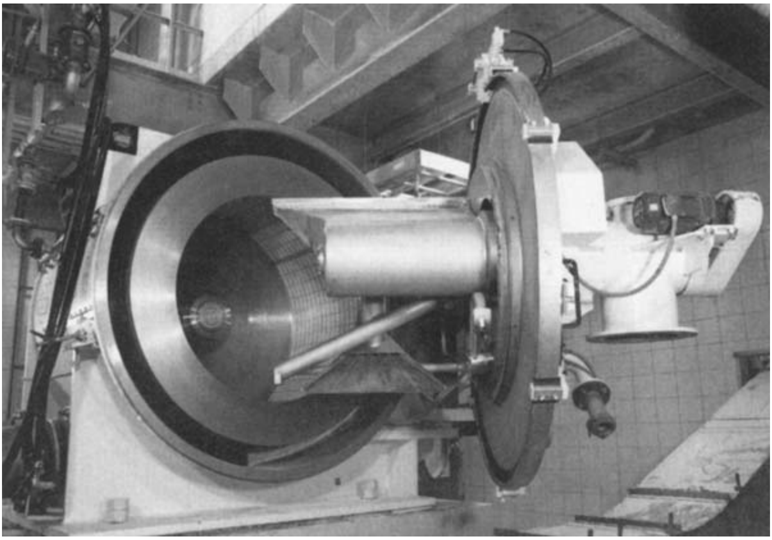


Figure 3.34 Peeler centrifuge internals

The dry spinning stage is completed after the wash liquor has passed through the cake and the dry solids are removed by the hydraulically activated peeling device, down to the residual cake heel. The peeled solids are removed from the basket through a chute or by a screw conveyor. The residual heel left in the basket after a batch of solids has been removed serves as the primary filter medium for the next cycle, and so on, until it becomes impermeable and needs to be removed by washing with filtrate.

Application examples for the peeler include bulk chemicals, fine chemicals and pharmaceutical products, petrochemicals, foodstuffs and related products. For pharmaceutical and fine chemical applications some peeler centrifuges incorporate fully automatic steam sterilization for clean-in-place requirements.

Centrifuges with rotary siphons are similar in many ways to conventional basket filtration centrifuges except that the filtrate, having passed through the cake and filter medium, is not discharged into the centrifuge housing, but flows through channels and holes in the basket bottom, directly into a ring-shaped siphon chamber, where it is removed with a siphon skimming pipe. An additional filtration pressure is then produced by the difference in level between the filter medium and the siphon position, thus increasing the filtration rate. The siphon chamber/basket area permits backwash liquid through the ring chamber into the inside of the basket. Liquid is forced to permeate the residual heel, and thus resuspends and regenerates it. At the same time, the backflush liquid creates a pool into which the next batch cycle is fed, thus ensuring that the solids are uniformly distributed. The manner of feed for this design reduces the likelihood of feed imbalance that can come with conventional centrifuges.

The imbalance can come with peeler centrifuges as the feed solids settle unevenly in the basket. The imbalance cures itself (flow is greater through the thinner cake areas), but can cause serious vibrations of the centrifuge for short periods. For this reason, vibration absorbers such as spring elements, vibration dampers or an inertia block should be fitted when the centrifuge is installed.

Moving bed centrifuges

In the fixed bed centrifuges just described, the separated solids form a cake in the basket that is stationary with respect to the basket while filtration is occurring, and the solids then have to be dug out of the basket in some way. In the moving bed centrifuges, on the other hand, the separating cake is continually moving across the surface of the basket, to discharge at the open end. In the fixed bed, the filtration cycle processes of feeding, draining, filtering, washing and dewatering take place one after the other through the establishing cake, but in the moving bed designs, these processes are happening all the time, but at different parts of the path from feed to discharge. The fixed bed centrifuge is thus a batch filter, while the moving bed machine is a continuous flow device (or very nearly so).

The basket of the moving bed centrifuge can rotate about a horizontal axis, or a vertical one (open end facing downwards). The closed end of the basket, at which the feed suspension enters, adjoins the drive mechanism, and the whole basket is enclosed in a casing designed to collect the liquids leaving along the basket, and the solids discharged at its open end, with a suitable baffle separating the two zones. (The casing can be sealed, to allow the centrifuge to work with organic liquids as the mother liquor, preventing the escape of vapours.) To aid the sliding motion of the separated solids along the surface of the basket, the filter medium is usually a screen made from wedge-wire bars, welded into the shape of a cone or cylinder, with the long side of the bars parallel to the axis of the basket.

Conical basket centrifuges

There are two main designs of moving bed centrifuge: those with a cone-shaped basket and those with a cylindrical basket. In the latter, solid movement needs mechanical assistance, but in the conical basket, the solids are potentially free to slide from the narrow end of the cone, which is where the feed zone is, to the wide end for solids discharge. The ability of the solids to slide in this fashion is dictated by the angle of repose of the solid particles, which varies from a quite high value when the solids are dry, to practically zero as a thin slurry. As the solids flow along the basket, the concentration of solids increases, and with it the repose angle. If this exceeds the angle of the cone, before the solids reach the end of the basket, then the solids will flow no further and will build up in the basket. If, on the other hand, this angle is not exceeded within the basket, then the solids will flow on to the edge of the basket and so out of it.

The dry angle of repose varies considerably among the range of solids that might be considered for separation in a conical basket centrifuge, and the manufacturer is thus faced either with having to make baskets with a different cone angle for each solid to be processed, or to find a way of controlling the rate of movement across the screen surface. There are some applications for which the large annual capacities justify the provision of a single angle cone, but, more commonly, flow control mechanisms are installed, enabling the centrifuge to be used for a range of feed slurries.

Solid flow control may be necessary to speed up the flow, of solids which have become too dry to reach the end of the basket, or to slow the flow down, for those slurries that would otherwise wash off the basket before they were sufficiently dewatered. A simple means of removing solids held in a basket (simple, that is, in operational principle, though not necessarily in mechanical structure) is to use a screw conveyor – which cannot be in contact with the basket or screen wear will occur.

Like the scroll discharge version, the other solid flow control machines are intended for a screen that has too shallow an angle for the solids to discharge, and then provide different mechanisms for acceleration. One of these uses torsional vibration (an acceleration-deceleration motion imposed on the basic basket rotation), and the amount of vibration is adjusted to give the required solid flow rate. Another version is the tumbling centrifuge, shown in Figure 3.35. Here the basket is tilted at a slight angle to the vertical axis about which it is rotating. In this way, each vertical slice of the basket makes a different angle to the vertical as it rotates, and therefore the solids on that slice are successively accelerated and decelerated towards the end of the basket.

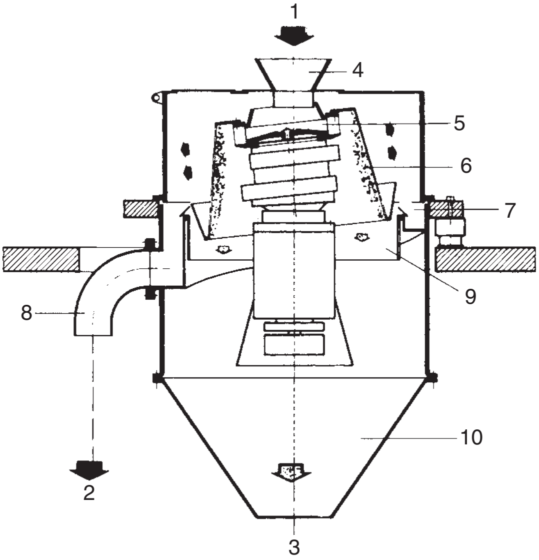


Figure 3.35 Tumbler centrifuge schematic. 1, Suspension; 2, filtrate; 3, solids; 4, funnel; 5, accelerator; 6, sieve basket; 7, filtrate channel; 8, filtrate connection; 9, rubber apron; 10, solids discharge housing

A different form of the conical basket centrifuge is found in the baffle-ring centrifuge. Here, the basket is divided into several frusta by a set of parallel rings protruding from the surface of the basket. This machine was developed for the dewatering of plastic granules, which is promoted by the impact between aggregates of granules and the baffle rings. The granules pile up against each baffle and then tumble over it onto the next section of basket.

Pusher centrifuge

The moving bed centrifuge with a cylindrical basket is known as the pusher centrifuge, and is one of the most common types of centrifuge for separating fast-draining crystalline or fibrous solids from suspension, at high throughput rates of solids. In its basic action, a layer of filter cake forms on the inside of the basket, near to the machine's feed end. This is then pushed along the basket (hence the machine's name) by a reciprocating plate, after which the plate withdraws to its rest position, allowing another ring of cake to form. On its next forward stroke, the pusher plate forces both rings towards the exit of the basket, then retracts, so that a third ring forms and so on.

In a typical machine, the feed suspension flows continuously from the stationary feed pipe, mounted at the axis of the centrifuge. It flows onto a rotating cone designed to accelerate the feed up to the rotational speed of the basket. From this accelerating cone, the feed flows over the face of the pusher plate on to the rear of the basket, as shown in Figure 3.36 (which actually illustrates a two-stage pusher). The bulk of the mother liquor drains quickly through the basket, and a cake forms and spreads out over the screen. The forward stroke of the pusher plate advances this layer of cake towards the open front end of the centrifuge as more solids are added to the cake. Then the return stoke of the pusher plate creates space on the screen, which is filled by more of the feed solids, so that the next forward stroke of the pusher plate acts on this new layer and pushes it and the previously laid material both forwards on the screen.

As the successive layers of cake are moved along the basket, excess mother liquor left adhering to the cake is removed by washing, using spray nozzles below the feed pipe. The reciprocation of the pusher plate is usually generated hydraulically, by means of oil pressure exerted on alternate sides of a piston situated on the push shaft. The necessary oil pressure is provided by a dual screw pump, the alternating pressure, on either side of the piston, being controlled by proximity switches.

The pusher may have one basket or more than one, in a multi-stage form as shown in Figure 3.37. In a one-stage machine, the reciprocating part is the pusher plate itself, carrying the acceleration cone. There is just one basket, and the plate moves back and forth over this basket and as close to it as possible, without wearing the screen surface. In a two-stage machine (shown also in Figure 3.37) the pusher plate does not move along the machine axis, and it is an inner basket that reciprocates. The front of this screen does the pushing of cake along the surface of the outer basket, and its return stroke leaves space free on the outer screen, which is filled by the solids falling over the front of the smaller screen as they are scraped along by the central, non-reciprocating carrier plate of the acceleration cone. The tumbling action over the front of the smaller screen helps to break up, and hence dewater, any agglomerates that may have formed on the screen surface.

The smallest and largest of the three screens in a three-stage pusher do not reciprocate, the pushing action being undertaken by the middle screen and the central plate carrying the acceleration cone. Four-stage pushers exist (for solids needing very efficient washing), and now stages 1 (the smallest diameter) and 3 reciprocate, while

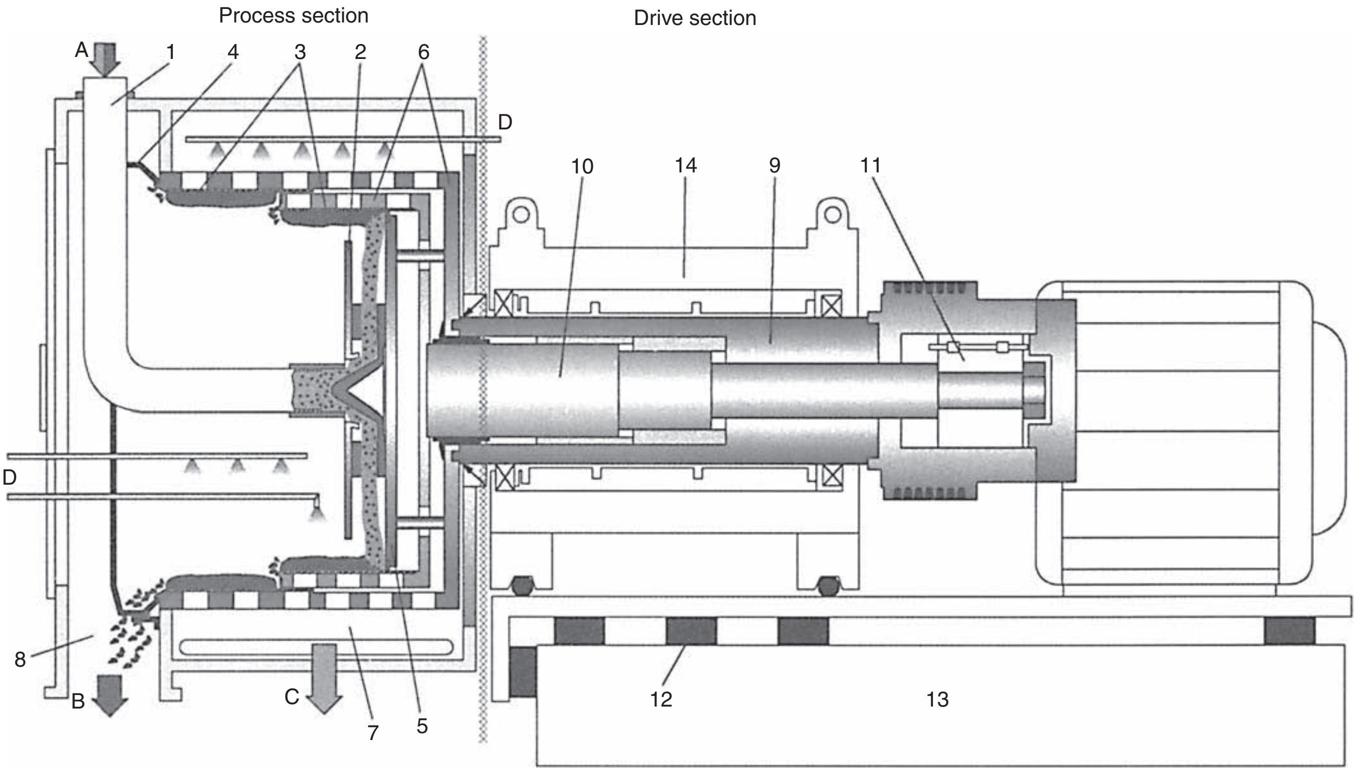


Figure 3.36 Pusher centrifuge schematic. A, Slurry; B, solids; C, filtrate; D, wash liquid.
Process section: 1, Feed pipe; 2, feed distributor; 3, slot screen; 4, volute race; 5, pusher plate; 6, basket; 7, filtrate housing; 8, solids housing.
Drive section: 9, Main shaft; 10, pusher shaft; 11, pusher control unit; 12, danger elements; 13, machine frame; 14, rotor with bearings

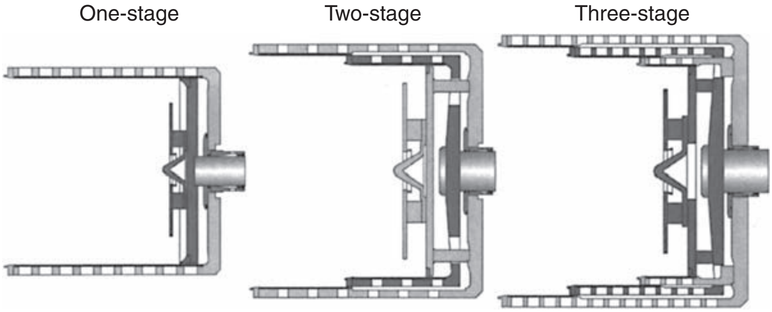


Figure 3.37 Pusher centrifuge rotors

stages 2 and 4, and the central disc, do not move axially. On the forward stroke, cake is shifted from stage 2 to stage 3, some is pushed off stage 4 to be discharged, and stage 1 is replenished. Then on the return stroke, cake is pushed from stage 1 to stage 2, and from stage 3 to stage 4. Washing is undertaken on stages 2, 3 and 4.

A more complex design of pusher, although saving of space where more then one machine is required, has the drive and push mechanisms mounted centrally on a common axis, with a basket at each end of the drive shaft. In this way, the forward stroke in one basket is the backwards stroke in the other.

3J. PAD AND PANEL FILTERS

From the complexities of the centrifugal filter, the Handbook moves on to one of the simplest forms of filter, used mainly for dust removal from air, in ventilating situations. These are the pad or panel filters, consisting of thick sheets of filter medium, or thinner materials folded to occupy the same space as a pad, contained in a rectangular frame and intended to fit tightly in a corresponding rectangular hole in a dividing wall. They are made in vast numbers, to standard dimensions (usually delineated in inches rather than metric dimensions), and intended to be used once and then discarded – or at most discarded after only a few use/clean cycles.

The purposes of dust filtration include:

- making or keeping a working or living space healthy to occupy and/or work in
- prevention of environmental air pollution, by capturing contaminant particles as they leave a manufacturing process, furnace or machine
- proper maintenance of machinery by preventing the ingress of dust particles that would damage the workings
- improvement of product quality, as in prevention of dust deposition on photographic film or semiconductor surfaces
- recovery of valuable dusts from a manufacturing process, that would otherwise represent economic loss
- bulk recovery of solids transported by air as in a pneumatic transport process
- protection of workers from hazardous dusts at or near their point of generation.

The proper management of dust collection follows a basic rule of any pollution control technology, namely that it is best to deal with a dust suspension as near to its source as possible, rather than after it has been diluted with gas from other sources. Thus, fume from a smelter should be treated in hoods immediately over the smelter, rather than in the general exhaust from the smelter building.

Dust characteristics

The requirements for dust filtration vary considerably with the particle size of the dust material, and with its concentration in the suspending air or gas (and also with the velocity of the suspending gas). Where the concentration of the solids is reasonably high, the most likely separator would be a cyclone, or even a simple settling chamber, which would also be used (at least as a first stage separator) when particles are present with diameters approaching 0.5 mm (500 μm). As was stated in Section 1B, some 90% by weight of all airborne particulate impurities range from 0.1 to 10 μm in size, although this range and the actual concentration of solids will vary markedly.

Some indication of the size ranges of various classes of particulate material is given in Table 3.4, from which it can be seen that dust collection is primarily concerned with particle sizes of 1 μm and above.

Table 3.4 Particle size ranges

Particle class	Diameter range, μm
Gas/solid	
Fume	0.001–1.0
Dust	1.0–500+
Gas/liquid	
Mist	0.005–10
Spray	10–5000+
Atmospheric	
Smog	0.005–2.0
Clouds & fog	2.0–60
Mist	60–200
Drizzle	200–500
Rain	500–10,000
Microbes	
Viruses	0.003–0.05
Bacteria	0.3–30
Soil (Earth)	
Clay	0.05–2.0
Silt	2.0–20
Fine sand	20–200
Coarse sand	200–2000
Gravel	2000–20,000+

As far as fine dust separation is concerned, it is the range of filters that is largely concerned, both the two types covered here, and those of Sections 3K and 3L.

Dust collection mechanisms include all of the entrapment processes described in Section 1C, with the effect of electrostatic forces also being very important in many systems. Filtration of dusts is achieved by depth filtration – for which the filter pad is very effective – and by the combination of surface and cake filtration that the pleated sheet media do so well. The two materials have vied with one another over the years as to which can achieve the highest degree of separation, a history of success that is largely determined by the development of new materials of one kind or the other.

Filter pads

The pad filter (often called a cassette) is a special case of the range of panel filters, all of which are made in standard sizes, to fit air-conditioning installations. The pad, as its name implies, is a thick flat sheet of fibrous filter medium, made either by wet-laying (as in paper) or by dry-laying (as in a felt). Felt pads are the most common, and they can be either as-laid, which would normally be the case for natural fibres such as cotton or wool, or needle-punched, for synthetic fibres.

These pads of filter medium are then placed in a containing frame to give them the necessary rigidity, and usually covered with a grille on both large faces (uncontained pads are also used, for example in aquaria). The covering grilles, made of wire mesh, expanded metal sheet or perforated sheet, give the necessary integrity to the finished element, especially in retaining the loose fibres at the pad surface, which would otherwise escape into the cleaned air flow.

The finished filter pad element is fitted singly, or in multiple arrays, into appropriately sized spaces in the dividing wall of a residential building or clean room. It is held in its space by a retaining lip around the edge of the space, on the downstream side of the element, or by clips or bolts if a more secure fixing is required. Ease of assembly, or of disassembly for cleaning or disposal, is obviously an important part of the system design.

A filter pad, which acts by depth filtration, will not easily be cleaned once it has accepted its full load of separated solid. It is possible that water washing, or the use of some other cleaning liquid, may extend its life, but it is normal to consider the filter pad as a disposable item.

Filter panels

The flat elements employing a thick filter medium and working by depth filtration, are distinguished here, as filter pads, from those using thin sheet media and working by surface filtration, which are called filter panels. The basic need of all kinds of filter is to maximize the available filtration area, and a single thin sheet would not present sufficient area to make it an economic concern. The solution is to corrugate the sheet by pleating it with concertina-like folds parallel to one long side of the panel, and with each fold as deep as the depth of the containing frame (as shown in Figure 3.38).

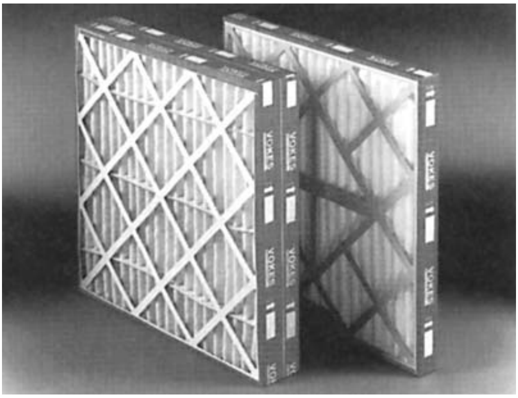


Figure 3.38 Panel filters with pleated media

The pleats can be formed at any spacing, to give the filtration area required. This can result in pleats that form a wide V-shape or a narrow U-shape. It is necessary to ensure that, whatever the pleat shape, the full area of the medium is available for filtration. The narrower pleats are at risk of pinching together, and thus losing effective area, so these will often be found with spacer sheets incorporated between the folds of the filter medium (as shown in Figure 3.39), where the spacer sheets are corrugated in a direction perpendicular to that of the filter medium.

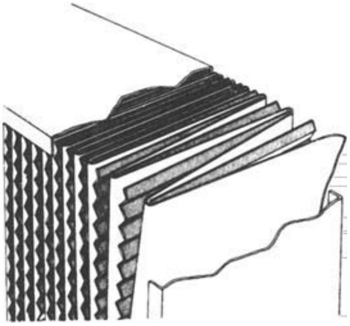


Figure 3.39 Pleated medium filter with spacer sheets

Panel filters can be made from any material that can be pleated, without cracking along the fold: cellulose or glass paper, fine wire cloth, woven fabrics, nonwoven fabrics of all kinds (felts, spunbonds, meltblown) and membranes. Charcoal cloth can also be used, provided that it is pleated before charring. Synthetic fibre media are most common, having shown themselves well suited to the ventilation of a wide variety of buildings: domestic, commercial, institutional and industrial.

Figure 3.40 shows a variety of filter pads and panels with their methods of construction.

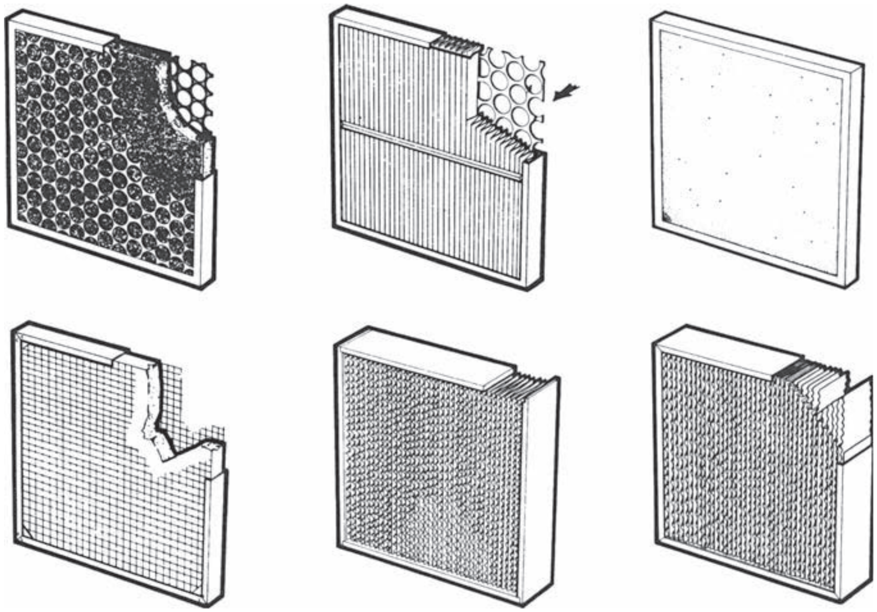


Figure 3.40 Filter pads and panels

The applications and efficiencies of dust collecting filters are given in more detail in Section 6, where it will be seen that filter panels can achieve very high filtration efficiencies. Such high efficiency filters are normally installed in series with a prefilter, using coarser filter medium, to remove larger particles from the inlet air, which would block the fine filter too quickly.

The panel filter, because it works basically by surface filtration (or by creating a thin cake on its upstream surface), should be cleanable mechanically (by a sharp rapping over a dust collection hopper) or by back washing with water or a suitable cleaning liquid (followed, of course, by careful drying). Some panel filters are quite expensive, so the ability to clean them and return them to functional use can be an important feature in their selection.

3K. BAG, POCKET AND CANDLE FILTERS

In the dry filtration processes that use pads or panels to capture dust, the filter surface is basically flat – one side of the filter sheet in a pad filter, or the upstream surface of a pleated medium panel. The group of filter types to be described next capture the dust inside or on the outer surface of a generally bag-shaped element, of circular or elongated oval cross-section. These three types – the filter bag, the filter pocket and the filter candle – are very important components of the dust collection equipment spectrum, but bags are also used in liquid clarification.

Bag filtration of liquids

Filter bags for liquids are effective in removing particulate contaminants in the processing of a wide variety of materials. Bag filtration is a pressure-driven operation, wherein the product to be filtered is forced through the filter unit. Such a unit would normally consist of the filter housing, a retaining basket and the filter bag.

Generally speaking, liquid bag filters are used for the same purpose, but for a finer degree of filtration than that for which the strainers of Section 3B would be used. They provide filtration systems for small solid particles of particle size in the 1–1200 micrometre range, with flow rates between 1 and 1000 m^3/hr and for low solid concentrations.

In operation, bags in the form of woven mono and multifilament fabrics, needlefelts or meltblown nonwoven fibres are fitted with a top seal arrangement to enable their location and sealing into a suitable housing vessel. In view of the potential high differential pressures that can develop across the bag, it is normal practice to provide, within the housing, a support framework of some kind, either a cage made of metal rods, or a basket made from perforated metal or wire mesh. The basket retains the bag in position and protects the system against the bursting of the bag. The basket can also be used to lift out a full bag when the filter is to be renewed. Figure 3.41 shows some examples of liquid filter bags, with support baskets.

Flow of contaminated liquid is usually from the inside of the bag to its outside, with filtration occurring on the inner face of the bag, predominantly by surface filtration (followed by cake formation), with a degree of depth filtration with felted media. Figure 3.42 shows the principle of operation of the liquid bag filter. (There is no strong reason why filtration should not occur in the opposite direction, with the bag supported on a cage – as is mostly the case with gas filtration in bag filters. The layer of collected contaminants now forms on the outside of the bag, from which it can be blown, by a reverse flow of liquid, to accumulate in the base of the housing, from which it is blown out periodically.)

Modern filter media technology has enabled filter bags to be manufactured in a variety of materials offering ratings of between 1 and 1200 μm. These materials include nylon, polypropylene, polyester, porous PTFE film and other fluoropolymers, viscose, aromatic polyamides, felts and woven wool. The filter bag was a very popular item for decades, but lost its popularity when finer filtration demands could not accept the uneven porosities represented by the holes in the stitched seam. The development of seamless bags in these various materials has restored the liquid bag filter to its earlier popularity. One piece glass-reinforced polypropylene all-plastic bag filters are extremely corrosion resistant, and can replace more expensive filters with plastic-lined housings in many applications; they can handle temperatures up to 50% higher than PVC filters.

Most liquid bag filters are of the single bag in a single housing type. Flow through such a unit must be stopped when the pressure drop across it indicates that the maximum dirt-holding capacity has been reached. Bag filters can also be used, in this polishing role, in a duplex housing, with two bags side by side, and piped so that each is either on-line, filtering, or off-line, being cleaned (as shown in Figure 3.43).

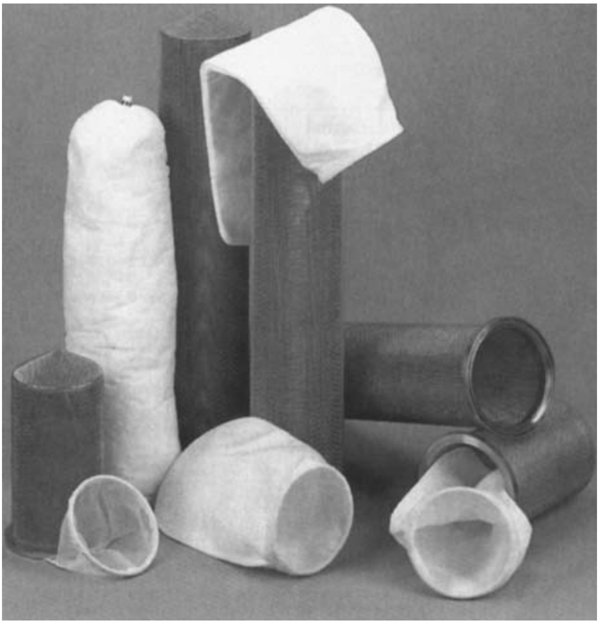


Figure 3.41 Filter bags and support baskets

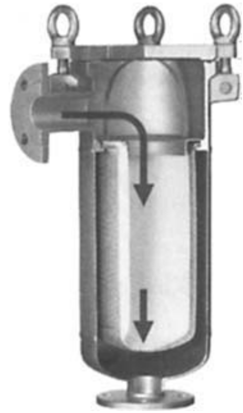


Figure 3.42 Operating principle of bag filter

Several bags can be housed in one vessel, supported from the same tube plate, and operated in parallel. This arrangement (very common in the bag houses used for gas filtration) is akin to a candle filter, and is described later in this section.

Figure 3.43 All-plastic duplex bag filter

Bag filters for gases

One of the most common sights in a power station or processing plant is the large chamber filled with an array of filter bags, known in some industries as a baghouse, and in others as a fabric filter. These are used on large exhaust gas streams, mainly to prevent pollution from dust residues, but quite often for the recovery of valuable solids from the exhaust.

Although perfectly usable on the scale, and in the sizes of, liquid bag filters, the corresponding units for gas filtration are usually much larger, and are used in the multiple element installations, because they usually have to deal with very high flow rates. For the small-scale treatment of gas streams, the pad and panel filters of Section 3J are most commonly employed.

The most common form for a gas filtering filter bag is a long, cylindrical sleeve or bag, mounted on a cylindrical cage made from metal rods, with support rings at regular intervals along its length. The bag is positioned vertically, usually with its closed end at the bottom, hanging from a support plate with its open end fastened to a corresponding hole in this plate. Access above the support plate, and the method of fastening to it, allows individual bags to be withdrawn for replacement if damaged or too clogged to be effective.

Dust capture can be effected on the inside of the bag (gas flow from inside out) or its outside (gas flowing from the outside), with the latter by far the most common, especially with the more automated baghouses. Dust cakes on the outside of the bag are more easily removed, either by shaking the bag assembly, or by a reverse flow of compressed air. Internally accumulated dust can be shaken into the bottom of the bag, but eventually the baghouse must be shut down and the bags removed for emptying.

Dust accumulated on the outside of the bags, when blown off the bag surface, falls into the hopper at the base of the baghouse. A large proportion of baghouse systems use a pulse jet blow-back (Figure 3.44), in which each bag has a separate valve from a compressed air supply above it, so that any bag can be blown free of

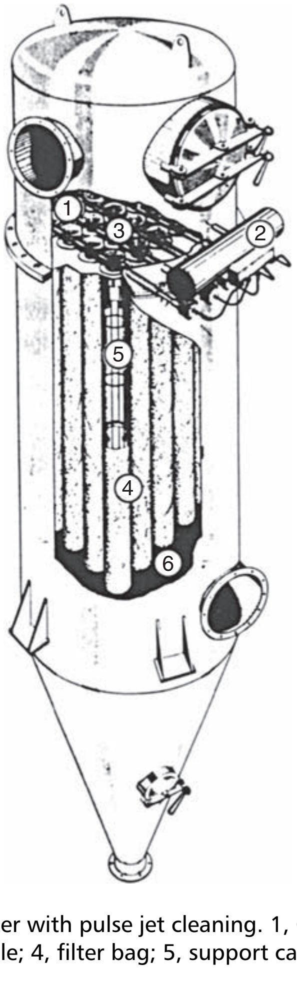


Figure 3.44 Tubular bag filter with pulse jet cleaning. 1, Clean gas duct; 2, compressed air; 3, jet nozzle; 4, filter bag; 5, support cage; 6, dirty gas chamber

accumulated dust cake, either a bag at a time in turn, or in small groups. In this way, the bags can be kept free of collected dust without the need to shut the whole baghouse down for the purpose. There is sufficient elasticity in the bag material so that the pulsed jet causes a slight expansion in the bag, which cracks the cake, making its release much easier.

The material of the bag, and the baghouse construction, can be selected to suit the nature and characteristics of the dusts to be handled. The main system parameters of concern are particle size and density, their abrasive nature and hygroscopicity, and their tendency to form aggregates. Also to be taken into account are the electrical properties of the particles, particularly if the dust suspension is potentially explosive. In this latter case, the chance of auto-ignition or explosion, triggered by a spark from electrostatic charges, can be eliminated by the use of anti-static media, such as synthetic fibres interwoven with metallic or carbon fibres, and with an earthed connection. Bag fabrics can also be treated for water repellence, to give fire resistance, and with special surface coatings either to improve filtration performance or give easier cake release.

For a considerable part of the history of the baghouse, the main material of the bags was a woven fabric, using natural fibres. Once felts became available with sufficient strength, at first plain felts laid on a strong scrim, and then needled, these rapidly took a share of the baghouse market, mainly on economic grounds. Felts had a more homogeneous construction, enabling a greater dust retention capacity, usually at lower pressure drops, but their greater depth filtration action required a more rigorous cleaning action.

Synthetic nonwovens, such as spunbonds and SMS sandwich media, are now an important component of the baghouse filter media, often pleated to accommodate more filtration area in a given housing (with a protective layer of very coarse mesh outside the pleats to retain them in position when the bag is backflushed).

The often hot nature of exhaust gases leads to the frequent use of PTFE/Teflon as the material for bag media, as well as the newer Tefaire (a needlefelted blend of 25% glass and 75% Teflon fibres). Other temperature resistant materials include a range of polyimide fibres, especially for minerals processing and cement production exhausts.

A very different type of element, although employed in the same type of structure and layout as the baghouse using bag filters, is the rigidized media element, developed in Germany by Herding. In place of the flexible fabric-style medium, the element is flat, with two long sheets of rigid porous plastic joined around the edge, and with each sheet deeply corrugated parallel to their long side, to increase the filtration area, as shown in Figure 3.45.

Pocket filters

The filter pocket is just as its name implies: two rectangular sheets of filter medium, placed side-by-side, joined together at three edges, the fourth being open. Pockets are used almost exclusively for air cleaning, in which function they act, literally

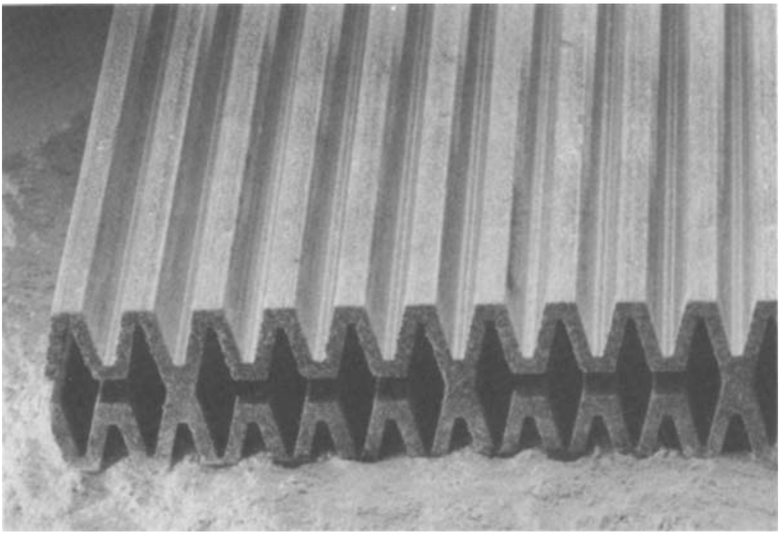


Figure 3.45 Section through rigidized medium filter element

and metaphorically, as an extension of the panel filters described in Section 3J: several pockets are mounted side-by-side across the front of the panel in such a way that the upstream face of the panel is almost completely filled by the open ends of the pockets, held open by the way in which they are mounted (as in Figure 3.46). The closed ends of the pockets extend out behind the panel into the clean air space. The individual pockets are removable for cleaning or replacement.

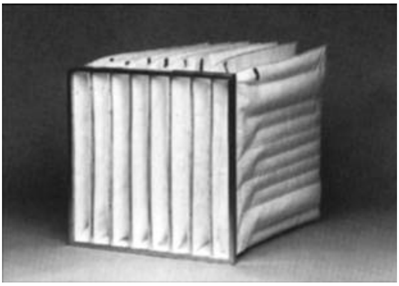


Figure 3.46 A panel with filter pockets

A pocket panel has between 4 and 8 pockets mounted across it, giving a high filtration area compared with the face area of the panel. The material of the pocket needs to be somewhat stronger than that of a pleated panel, but a wide variety of materials can be used, increasingly of synthetic fibre. Multi-layer construction is used a lot, featuring an inner layer (facing the incoming air) with larger pores to capture the coarser particles, a middle layer for fine filtration and a very fine outer layer to prevent fibre migration from the pocket.

Candle filters

There is much confusion over the precise meaning of the term ‘candle filter,’ so let it be said that, in the present context, a candle filter is a process filter, mainly used for the recovery of process residues from liquid streams. It almost always has a vertical cylindrical housing, inside which a multitude of cylindrical filter elements, closed at the bottom end, are suspended from a tube plate. Flow of liquid is from the outside of the element to its inside, and thence through the upper, open end of the element into the filtrate space above the support plate. Some typical arrangements for a candle filter are shown in Figure 3.47.

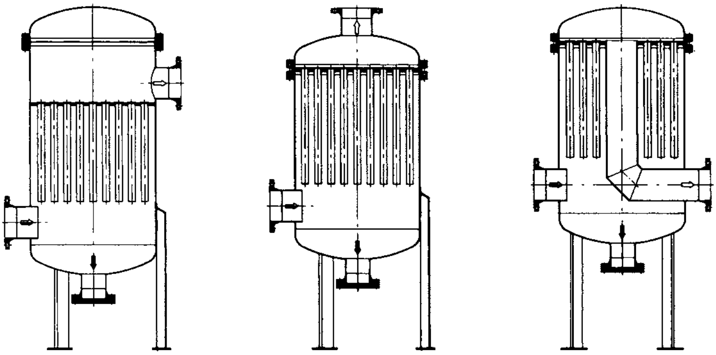


Figure 3.47 Candle filter arrangements

The filtering element can be almost any kind of cylindrical structure, but is ideally a rigid, smooth-surfaced tube of porous metal, plastic or ceramic. Such media are available for filtration down to very low levels of particle size, and at the same time are self supporting (and so able to hang securely from the tube plate) and strong enough to resist quite high pressure drops across them. (Whilst the hanging orientation is by far the most common, the filter’s name implies an earlier usage, mounted upwards from the support plate, and thus resembling candles in a candle holder.) Candle filters with ceramic candles are widely used for the filtration of aggressive gases as well as for hot corrosive liquids.

With that definition of a candle filter understood to be the basic one, it must be accepted that the term is used of any multi-tubular filter with hanging elements. These elements can be almost any kind of cartridge filter. A tube plate with an array of cartridge elements is shown in Figure 3.48.

A filter that resembles a candle filter is the Cricket filter (from Amafilter), which is so-named because the elements, rather than being cylindrical, are flattened so as to resemble a cricket bat in shape. Each element was suspended from a filtrate collection manifold to which was connected an internal filtrate pipe rising from the bottom of the element. The small volume of each element and the flat surface ensured complete cake removal during blow-back.

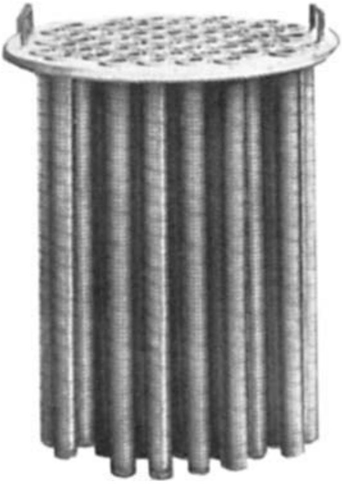


Figure 3.48 Tube plate and candle array

3L. CARTRIDGE FILTERS

Several attempts have already been made in this Handbook to classify a type of filter, only for examples to be shown of filter types that cross the filter type classification boundary. The difficulty of precise classification is nowhere so apparent as in the types of filter elements known as cartridges, and therefore with the types of filter termed cartridge filters.

The essential features of a cartridge filter include a cylindrical housing, usually pressurized to handle the pressure in the fluid being filtered (but vacuum operation is not ruled out), in which sits a replaceable filter element, which is the cartridge. This element is also basically cylindrical in shape, and most types are made to a set of standard lengths and diameters, so as to be able to be incorporated in a standard housing. It is most common for the cartridge filter to be set up as a unit with one housing containing one cartridge, but where continuity of fluid flow is essential, then a duplex system is used with two cartridge filters in parallel, piped so that one unit is in use while the other is off-line being cleaned, whereupon the flow is switched to the now cleaned unit, and the other is taken off-line.

The cartridge filter is used almost entirely for clarification, the cleaning of a fluid from contamination, and the fluid is most often a liquid, with contaminant levels of less than 0.01% by weight (i.e. less than 100 ppm). However, some baghouses for solids recovery from gases now use cartridges as their filter elements. A dust filter with large diameter pleated cartridges is shown in Figure 3.49.

Cartridges are available in a very wide range of types, and in almost every type of filter medium. However they can be broadly classed into two types, according to their construction, which can easily be distinguished, although even here there are formats that bridge this classification. The first uses an integral piece of porous

Figure 3.49 Cartridge elements for dust collection

filter medium, made or formed into the required cylindrical shape, while the second is made of sets of components that are not necessarily porous but become so when assembled together, with a porosity dictated by the nature of the components (rings, discs, ribbons, etc.) and by the tightness with which they are held together.

It should, of course, be noted that this definition of a cartridge filter could include several other types of filter element that have been described under other classes of filter:

- the basket strainers described in Section 3B
- the filter bags described in Section 3K
- the filter candles also described in Section 3K
- most of the automatically operating (self-cleaning) filters of Section 3M use cartridges as their filter elements
- and even some of the membrane modules described in Section 3S can be considered as cartridges.

Equally, there are one or two types of replaceable element filter that do not fit the precise definition of a cartridge filter given above, yet are included here because of their similarity of function. These are the capsule filters, much used in laboratories and small-scale production processes such as are involved in the pharmaceutical and life science sectors, and the polymer melt filters, employed to ensure the freedom from blockage of extrusion nozzles for polymer fibres and filaments.

Cartridges are made to work by surface or depth filtration, the choice between which is dependent on a number of factors. Filtration performance can range from

0.5 mm down to 0.1 µm or even less where membranes are used for the filter medium. For a long time, surface filters have been graded according to an absolute rating, and depth filters according to a nominal rating and various levels of filtration efficiency. This, however, is changing with the introduction of absolute-rated depth filter media.

There is no universally accepted system for determining the removal ratings of cartridge filters in liquid service. The filter rating method known as the OSUF-Z test developed (at Oklahoma State University) for use with lubricating and hydraulic liquids has received wide acceptance, and has been adapted by some manufacturers for use with water. Nominal filtration is typically described in percentage terms as between 80 and 90% efficient at some specific particle size. The absolute rating can mean anything between 98 and 99.99% efficiency, or higher. Test methods and standards for filter media are described in detail in *Handbook of Filter Media* (Derek B. Purchas and Ken Sutherland, 2002, Elsevier Advanced Technology, 2nd Edn).

Integral media cartridges

The cartridges consisting of a single piece of filter medium are made from a perforated cylindrical core, of metal or stiff plastic, onto which the material of the filter medium is placed or formed. There are two basic types of integral media cartridges, depending upon which primary filtration mechanism is operating: thin media, which work by surface filtration, followed if necessary by cake filtration on top of the surface layer; and thick media, which work by depth filtration.

Thin media

The thin media can be any material that may be produced in sheet form, but a flat sheet wrapped around the central core would not be a very efficient filter element, because the ratio of filtration area to housing volume would be too small. The available area can be greatly increased by pleating the flat sheet in concertina folds parallel to the element's axis – some pleated media cartridges are shown in Figure 3.50.

Pleated media cartridges are a very popular form of filter element, being able to be manufactured from any sheet material with the required filtration efficiency that can stand the stresses of the pleating process without cracking. So they are available in:

- paper, both cellulose and glass
- woven fabrics, both mono and multifilament
- thin felts
- fleeces of nonwoven plastics, spunbonded and meltblown, and
- woven wire mesh, both plain and sintered.

Pleated cartridges are also produced with sheet membrane as the filter medium, but considerable care must here be taken to avoid cracking of the membrane along the folds of the pleats.

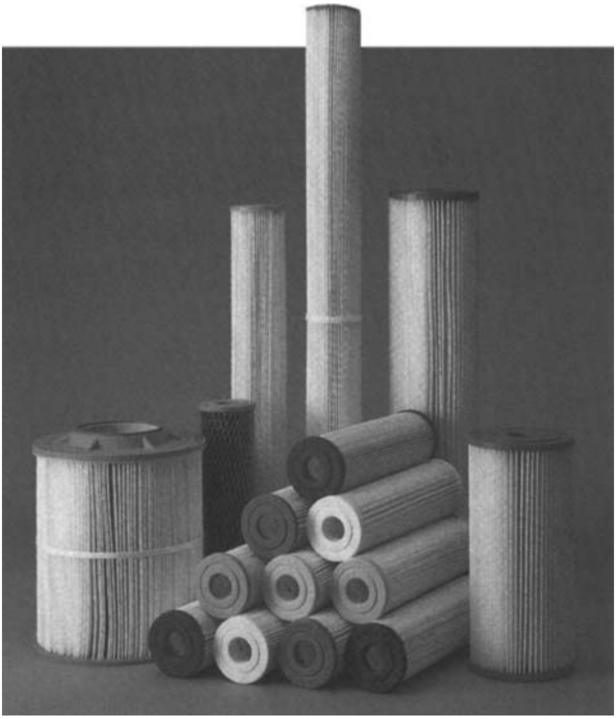


Figure 3.50 Pleated sheet media cartridges

The actual medium in a pleated cartridge will have protective mesh (wire or plastic) on its inside and outside, the whole being further protected by a cylindrical perforated plate screen external to the pleats (Figure 3.51). This figure also shows the end-caps sealed to the top and bottom of the pleats to make a coherent filtering element.

As with any pleated medium, but especially so when the pleats are to be formed into a cylinder around the centre core, there is an optimum number of pleats per unit length of core circumference that can be installed, before the parts of the pleats closest to the core become poorly used for filtration, either because the inter-pleat gaps get pinched closed, or because the pressure drop entailed in getting to the bottom of the pleat becomes too high. These factors then negate the benefits of the extra filtration area created by the pleating. It may therefore be necessary to interleave the pleats with strips of corrugated material (with corrugations at right angles to the direction of the pleating) to keep the pleats apart.

An alternative means of avoiding the loss of filtration area by the pinching of the pleats at their inner fold is shown in Figure 3.52. Here, in a system developed by 3 M, the pleats are at right angles to the axis of the cartridge. Made from polypropylene, the finished element has up to more than 60% greater filtration area than a depth filter cartridge of the same volume.

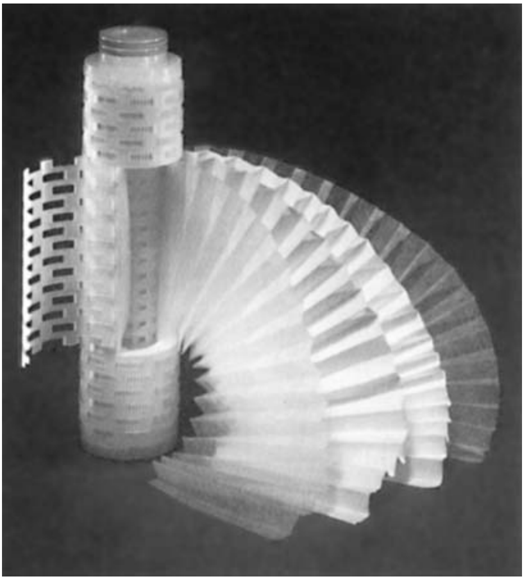


Figure 3.51 Pleated medium construction

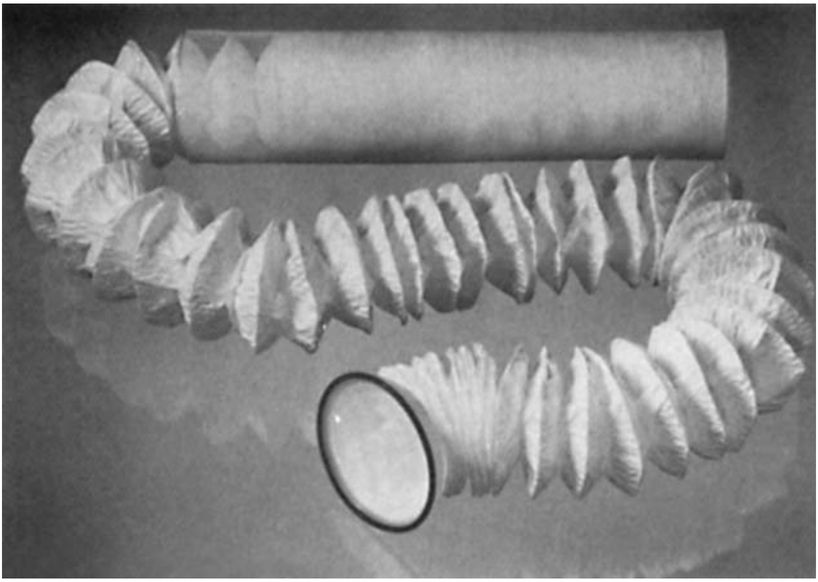


Figure 3.52 Cartridge with transverse pleats

The pleated cartridges are intended to work by surface filtration (hence the need for as much surface area as possible). If necessary a thin cake is allowed to form on the medium surface, so long as it does not fill the space between the pleats, and the cartridge is changed or cleaned before this occurs. As the medium has a finite thickness, some penetration of particles into the depth of the medium is possible, and if these are not removed by cleaning (by backflushing or washing in an appropriate cleaning liquid), then eventually the medium will become blocked and need to be discarded.

Thick media

The cartridges with thick media are intended to work by depth filtration, and their contaminant loading capacity is an important feature of their usability. Thick media will often be graded so as to have an increase in density towards the centre of the cartridge, thus improving their depth filtration behaviour. Once the maximum load has been accepted then the cartridge will normally be discarded, unless a high proportion of the collected contaminants can be removed by backflushing.

The thick media cartridges can be formed in a number of ways:

- if sufficiently flexible, the medium can be made as a flat sheet, then cut to the correct size and wrapped around the core, before the two edges are sealed together
- the medium can be made as a sleeve, which is then cut to length and slipped over the core (although some sleeves are self supporting and do not need a core), or
- the basic material of the filter medium can be deposited on the core, to the required thickness, and then finished as necessary to give the required filtration properties.

Whichever of these manufacturing techniques is used, the resultant elements will look roughly the same: a cylindrical layer of porous material between two end-caps (one sealing closed one end of the cartridge, the other with appropriate connections to carry the filtrate out of the filter), ready to be fitted into a housing of the appropriate size. The cartridges are made in a range of lengths and diameters, mainly interchangeable among the available housing sizes.

Almost every kind of material can be made into the thick medium used on these cartridges, including:

- unbonded fibre, as a felt or a needlefelt (mainly natural fibre, which has the necessary fibre adhesion)
- woven multifilament yarns of natural or synthetic fibre, wound as a sheet with several turns on the core to give a porous medium of the required thickness
- resin (i.e. adhesive) bonded fibre, moulded to shape, in a mass that will need to be cured (to set the resin), employing fibres of cellulose, glass or plastic
- thermally bonded (i.e. sintered) fibre, of plastic, metal, glass or ceramic
- resin-bonded plastic granules
- thermally bonded or sintered granules of plastic, metal or ceramic, and
- foams of metal or ceramic.

An important group of polymeric fibre or filament media is that where the extruded plastic (spunbonded, meltblown, electrospun) is dry-laid directly on to a rotating cylindrical core to make a medium that is as thick as required. This also enables the fibre density to be varied with the depth of the fibre layer, giving a coarse structure at the medium surface, with finer pores towards the centre.

Sintered media

The sintered (thermally bonded) materials will normally be made into tubular shapes, by moulding or isostatic pressing, before sintering, and these shapes will be self-supporting, so there is no need for a core (unless required in the forming process). These shapes can then be considered as candles rather than cartridges, a single element in its housing probably being called a cartridge, and a multi-element housing called a candle filter.

Porous plastic elements are sintered by special methods from high molecular weight thermopolymer powder. The pore size and filtration characteristics are controlled by careful selection of cryogenically ground powder to give a particle retention in the range from 5 to 200 µm. The elements are manufactured in specially designed individual moulds and most shapes are possible. Porous plastic elements are used for compressed air filtration and for general use in environments where temperatures do not exceed 80°C. An array of porous plastic elements is shown in Figure 3.53.

Figure 3.53 Sintered plastic powder elements

Sintered metal filters provide the possibility of closer control of pore size, shape and uniformity than can be achieved with plastics, and the resulting matrix is much stronger, more rigid and more resistant to heat. Pore sizes may range from submicrometre dimensions up to as much as 1 mm. Thus, theoretically at least, virtually any cut-off down to the finest ultra-fine filtering requirements can be provided by a sintered metal powder element. In practice, however, this range of application is modified by the increasing resistance to flow with diminishing pore size, which naturally tends to decrease porosity.

Porosity, or the proportion of voids to overall matrix volume, can be controlled over a wide range with sintered metal elements. Whilst increasing porosity decreases resistance to through-flow, the strength of the matrix decreases rapidly. For reasonable mechanical strength, it may be necessary to restrict porosity, by adopting a suitable compromise based on strength/permeability requirements. In the case of filter elements, porosity may range up to 70%, or possibly higher for low pressure drop elements. The particular advantage of sintered metal filter elements, apart from the fine cut-off that can be provided, is their high strength and rigidity compared with non-metallic media, which makes them particularly attractive for high pressure applications.

Sintered powder metal filters fall broadly into two categories: those produced by sintering loose powder in a mould, and those produced by compaction. Spherical particles are preferred for either, because they pack more uniformly and thus provide more uniform pore sizes. Spherical particles are relatively easy to produce and classify by spray atomization and sieving. The coarser grades of sintered metal filters are produced from particles with a particle diameter of about 1 mm. Since pore size is usually about 15% of the particle diameter, this would yield a pore size in the material of 150 μm. Such sintered metal filters are expensive to produce and thus not competitive at this level with wire mesh. Manufacturing costs of sintered metal filters are rather less with smaller particle diameters, whereas the cost of woven wire mesh increases with decreasing pore size, while mesh strength and rigidity are reduced.

Sintered metal filters become increasingly more competitive from pore sizes of about 100 μm downwards. At the finer end, however, spherical metal particles of the order of 5 to 10 μm diameter are expensive to produce and costly to classify although they have been produced down to 1 μm in size. Some typical porous metal elements are shown in Figure 3.54.

For most general purposes sintered bronze filters are suitable. For particularly arduous duties involving very high pressures, high temperatures or corrosive fluids the filter elements may be sintered from stainless steel, Monel, pure nickel, Hastelloy, titanium or even tungsten. Bronze and cupro-nickel sinter readily at low temperatures and thus a whole variety of shapes can be produced directly from metal powder in stainless steel or carbon moulds. The mould is passed through a furnace with a protective atmosphere to sinter the powder. Pressed or machined shapes may require subsequent treatment to open up surface pores. The elements can be machined to closer tolerances than can be produced by direct moulding, but

Figure 3.54 Sintered metal powder elements

machining should only be used for non-effective areas of the filter element such as the finishing of shoulders for registration purposes. Although these conventional methods of moulding are still widely used, the introduction of iso-static pressing has meant that a much wider variety of shapes and sizes can be produced.

Porous stainless steel elements may be employed where high strength, greater resistance to temperature and high resistance to corrosion are required. Porous stainless steel elements are commonly produced in the form of plates or discs used directly for filter element construction. The material commonly employed is a stainless steel equivalent to BS304S15, but with a maximum carbon content of 0.05%. Where the solid metal is subject to attack, corrosion of the porous metal will be greater because of the greater surface area exposed. The fine filtration provided by sintered metal elements, together with the controlled porosity ensuring a true absolute rating, makes them an attractive choice for high duty, high temperature applications.

The metal cartridges described above are based on metal powders, but it should be noted that sintered metal cartridges are also available made from metal fibre and wire mesh. Both materials are sintered to give the necessary integrity of the medium (and, in the case of wire mesh, to maintain the precision of the apertures formed in the mesh when it was woven). Wire mesh elements are usually pleated and used for the thin media tasks described earlier, while sintered mesh cartridges operate by depth filtration. Wire meshes can be laminated and then sintered together to make a thick medium with precise variations in pore size through the medium. The sintered fibre elements typically have higher flow rates for a given pressure differential, and a higher dirt-holding capacity than powdered metal elements with the same rating. Sintered fibre materials can be made thin enough to pleat, thus providing excellent filtration as a cartridge. As with powdered metal elements, the fibre and mesh cartridges, when fully loaded with contaminants, can easily be reclaimed by backwashing, ultrasonics or chemical cleaning.

Ceramic powders can be sintered into a wide variety of porous shapes for use as filter elements. In the form of porous pottery, ceramics were one of the earliest materials used for filtration. Porous ceramic filters for use as cartridges are generally in the form of a plain cylinder with a thick wall, the thickness of which provides the depth of filter medium for retention of the solids in a filtration process. As far as tubular elements are concerned, these are either plain cylinders (i.e. open at both ends) or flanged candles (i.e. candles with a flange on the open end for fixing in the cartridge housing or to the tube plate of a candle filter).

Sintered ceramic element sizes vary widely, with one-piece elements available in lengths in excess of 1 m. Operating temperatures of 900–1000°C are practicable, and with a more refractory bond ceramic candles can be used up to 1600°C. Pore sizes range broadly from 100 μm to 1 mm, with average porosities of 35 to 45%. In terms of chemical resistance, ceramics are used in the 1–9 pH range (it should be noted that the chemical resistance of a ceramic medium is dependent on the operating conditions and should be carefully checked for each particular application). The versatility of porous ceramic media makes them particularly effective for a wide range of filtration applications.

Capsule filters

Similar in principle to the cartridge filter, by virtue of being used until full of collected solids and then cleaned or discarded, are the small in-line capsule filters, much used in laboratories and the small-scale production processes of the life-science industries. These are made entirely, both housing and filter medium, of a polymer suitable to the operating conditions. They take the form of short cylindrical housings (with a length of the same order as the diameter), closed at each end, except for a nipple or nozzle that can be connected to a plastic flow line.

The capsule is inserted into the flow line, the process is run and then the filter is removed and discarded if it was removing contaminants, or its solid contents recovered if they are valuable.

Polymer melt filtration

Somewhat akin to the capsule filter in operating principle, although very different in construction and operating conditions, are many of the filters used to remove contaminants from the flow of molten polymer on its way to an extrusion nozzle.

The filtration of plastic melts presents a considerable challenge, and sets of standards have had to be introduced to meet the demands set by customers in the plastics processing industry. In particular, for a long time filtration over large surface areas could only be carried out using cartridge filters or filter screen packs with inherently unsatisfactory conditions in the melt channel.

As demands have grown for finer degrees of filtration in available filter media, the extruded fibres used in these media must also be made to a smaller and smaller diameter. This means that the extrusion process must produce smaller diameter material, and so the nozzles must be finer, which makes them more easily blocked by contaminant particles – unless these, in turn, are filtered from the melt. The filter media used for this task of polymer melt filtration have been discs of sintered powder, fibre or mesh.

Changing the medium employed in polymer melt filters required lengthy production interruptions, increasing material costs and lengthening the cleaning process. To overcome these and other manufacturing difficulties, continuous screen-changer disc filters have been developed where the filter disc rotates between two plates (Figure 3.55).

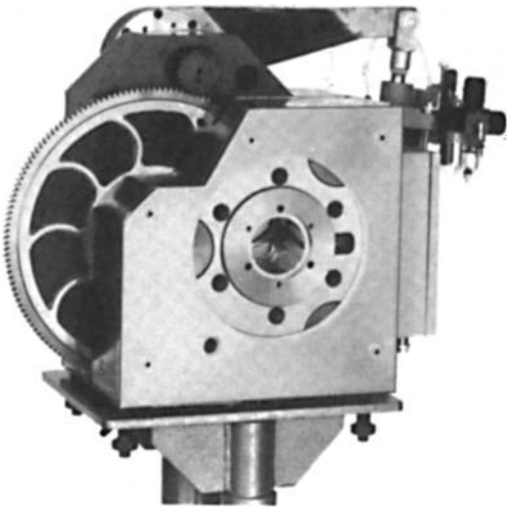


Figure 3.55 Polymer melt screen changer

At present, rotary disc technology is the optimum solution for the filtration of high or low viscosity plastic melts. Constant production is a top priority for efficient manufacture of high quality plastics and rubber products, but efficiency of use and return on investment should also be primary considerations. The continuous screen-changer for constant melt filtration under control constant pressure has proved successful for filtering most extrudable thermoplastics, including polycarbonates, PPS, PEK and PVC. Melt pressures of up to 700 bar and temperatures up to 450°C can be dealt with, and screen surface areas range from 8–500 cm^2.

Foams

A foam is created when a mass of gas bubbles is evenly distributed throughout a quantity of liquid, in such a way that the gas occupies almost all of the final volume, surrounded by the liquid in the walls of the bubbles. If the liquid then sets solid, a very porous mass is created, which would, in principle, make an excellent filter medium. Unfortunately, in the frozen state the bubbles are not interconnected, so no fluid flow through the foam is possible.

However, if the foam is reticulated (treated with combined thermal and chemical processing), the material in the bubble walls retracts to the nodes of the original bubble network, creating a very porous mass with almost all of the pores interconnected. The pore size is determined by the original bubble size, and quite a considerable variation in this size is possible.

Thick media cartridges can then be made by fixing a layer of plastic foam to a perforated core. A major alternative use is the formation of coarse ceramic foams, as discs, to be used as filters in the removal of contaminants from molten metal.

Constructed cartridges

The final group of surface filtering cartridges is made up of individual components that, by themselves, could not act as a filter medium, but when assembled into a generally cylindrical shape create an external surface carrying an array of slots, whose width defines the pore size of the filter. Probably the simplest such array is a set of circular discs stacked one above the other around a central former, which is hollow and perforated to act as filtrate off-take. Each disc has a number of slight pimples on one side so that when they are clamped together there is a narrow circular slot at the periphery between each adjacent pair of plates, which can be made of plastic or metal. This cartridge sits in a cylindrical housing that provides the means of holding the plates together, with flow of liquid through the stack of discs towards the filtrate collection pipe. Contaminants are removed down to a very precise dimension, set by the slot width – except, of course, that larger particles will get through if they are needle or plate shaped, so it only works well for granular particles.

The same 'metal edge' effect is produced by using a spring in the form of a continuous flat ribbon wound in a helical shape. With pimples on one side, and with the spring fully compressed in the cartridge housing, one long continuous slot is formed, which has the same precise cut-point (and the same limitations about non-granular particles). Now, however, if the compression of the spring is relaxed, the adjacent turns move apart and collected dirt can easily be dislodged, from the outside of the stacked ribbon but also from between the turns.

The ribbon can also be in the form of a continuous strip of wedge-wire, wound into a helix in a similar fashion, and with dimples to provide the required spacings between the turns (as in Figure 3.56) – but wedge-wire rings can also be formed into a metal edge element if placed one above the other and welded to a support

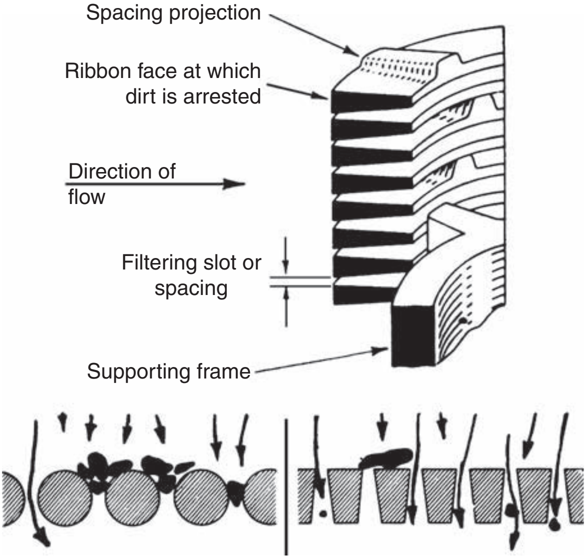


Figure 3.56 Wedge-wire edge filter. Bottom left: particles can jam in screen; bottom right: particles than can enter, will pass through

structure appropriate distances apart. In either case, the broad face of the wedge is placed on the outside of the cylinder, to create the surface filtration medium.

The stack of discs is replicated in another form where the discs are circles of paper of the full diameter of the final element. Between each pair of discs is set another disc of paper of smaller diameter and high porosity through which the filtrate flows, leaving any contaminant on the outer surface of the stack or held in the annular spaces between the main discs.

The spiral effect of the ribbon is reflected in the wire wound cartridge in which a wire is wound in a close spiral around the core to form a filter medium working entirely as a surface strainer. The turns of wire are set in grooves machined on the core, so that there is a precise slot between adjacent turns of the wire. The wire may be of metal or made from a single filament of polymer.

The spiral wind is also a characteristic of the yarn-wound cartridge. A multifilament yarn is wound in spiral fashion around a coarsely perforated core. Upwards of 20 layers of yarn are placed on the core, with successive turns at a pronounced angle to the circumference of the forming cylinder, and with this angle reversed in successive layers. The resulting effect is to create a mass of diamond-shaped apertures, and a very tortuous path for the liquid in its flow through the wrapped yarn (Figure 3.57). This gives a very effective depth filter, with filtration not only in the apertures between the turns of the yarn, but between the fibres in the yarn as well. The yarn may be of natural or synthetic fibre.

The specific advantage offered by the yarn-wound cartridge is that of compactness – a high filtration area to cartridge volume ratio: a 250 mm long by

Figure 3.57 Yarn-wound cartridges

50 mm diameter yarn-wound cartridge having the same filtration area as a surface filter of over 300 mm diameter. The yarn-wound cartridge was one of the first to be made in standard dimensions, able to fit into housings from a variety of manufacturers, and was a major form of filter cartridge for a long period. Available lengths are 250, 500, 750 and 1000 mm, and housings are available in plastic and metal. Such cartridges are made with pore sizes normally ranging from 1 to 100 µm, and quite coarse pore sizes can filter down to very much smaller limits because of the depth filter action.

A quite different filtration medium is created in another stacked disc filter. Here the discs are quite flat and are held together by compressing springs. However, in the flat surfaces of each disc are machined a set of grooves with a triangular cross-section. These grooves run from the centre of the disc to its periphery, but at an angle to the radius, and this angle is in the opposite direction on the two sides of the disc. Thus when the discs are clamped together a large number of groove intersections are created. The irregular path for the fluid along a groove, then through an intersection, with a choice there of which grooves to follow, makes for many sharp changes of direction for the suspended particles, with a high probability that solid particles will be trapped at the intersections. The number of intersections is determined by the groove/radius angle. When the stack is full, the pressure holding the discs together is relaxed, allowing them to be spun by the incoming jets of liquid, and so release the trapped solids. This type of filter is used for the straining of process and working fluids.

Lenticular discs

A constructed cartridge somewhat different from those just described is the lenticular disc filter – the prime difference being that the components of a complete element are capable of undertaking filtration on their own, and are in fact used in that way. The lenticular disc is a circular element made from two discs of filter medium joined around their outer edges and separated at the centre by a filtrate offtake tube, to give the disc the shape of a lens for which it is named. The disc can be used independently, in an appropriately shaped housing, but more often several discs are mounted one above the other (as in Figure 3.58) on a common filtrate pipe, and then placed in a cylindrical housing as a cartridge. This format has been successfully used by Cuno for its ZetaPlus charged media filters.

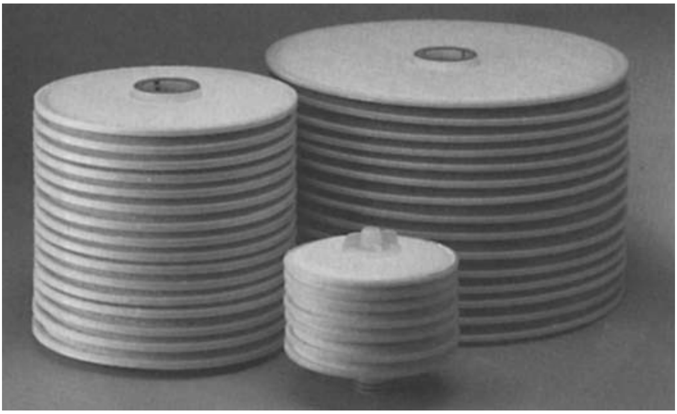


Figure 3.58 Lenticular disc cartridges

3M. BACKFLUSHING AND SELF-CLEANING FILTERS

Most filter elements, including all of those described in Sections 3K and 3L, are intended to be cleaned free of accumulated contaminants, wherever this is possible, simply from the economic viewpoint of avoiding waste. This is done either by removal from their housings for cleaning in another place, or by cleaning *in situ*, but only after stopping the flow of process fluid through them.

Primarily, the backflushing/cleaning process is employed to maintain a dirt removing filter in good working order. However, it is also used to recover solids collected on the element surface, when that is the purpose of the filter (in some baghouses, for example, or in pressure leaf or plate filters). These process applications are described in the place appropriate to these filters, and this part of Section 3 deals with the cleaning of clarifying (contaminant removal) filters.

Backflushing filters

The most common form of cleaning is to reverse the flow of fluid through the filter medium, and so to blow the surface clear of collected contaminants. As this requires filtration to stop, a satisfactory system employs at least two filters, side by side in a duplex arrangement, with the piping and valves around the filters such that the main flow can be switched from one filter to the other when full of dirt, after which the dirty filter is backflushed to wash all of the collected contaminants off the filter element. Figure 3.59 shows such an arrangement, but with three elements.

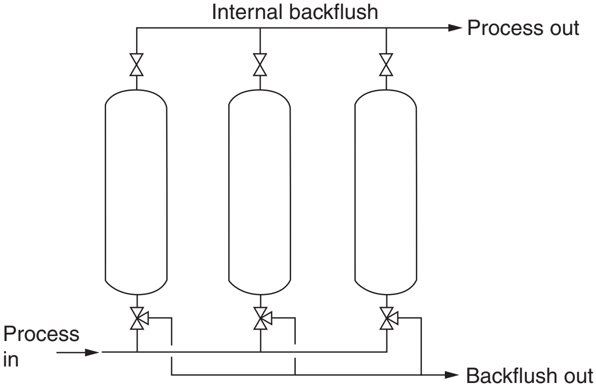


Figure 3.59 Backflushing arrangement

The backflushing can be described as internal when some of the filtrate is redirected for the washing duty (as in Figure 3.59), and external when a fluid other than the filtrate is used as the backflush agent. A combination of fluids may be used as the backwash, and these may include compressed air. In some applications, it is necessary to use compressed air to complete the cleaning of the element.

Cartridge backflushable filter systems, with suitable elements, can be used to filter a wide range of liquids, from water to various chemicals, including toxic materials. They are essentially polishing filters with a low dirt-holding capacity. Hence they should only be used where the contaminant loading is under 1000 ppm. While higher contaminant loadings could theoretically be handled, other types of filtration system or solid-liquid separation method would normally offer more economical alternatives.

Backflushable filters generally rely on the liquid velocity to clean the filter medium. This usually limits the use of these systems to low viscosity liquids (up to 50cp). While this is generally true, there are applications where backflushable systems operate very well with fluid viscosity as high as 50,000cp. In these cases, fluid velocity is almost certainly not a major factor in cleaning the filter medium.

Cartridge backflushable systems operate as closed systems. As a consequence, they can be used in applications with toxic or hazardous fluids with a minimum impact on the environment.

Contaminant loading considerations manifest themselves in their effects on the filter area required, the interval between backflushes, and the type of backflush system (internal or external) that is needed. The minimum practical interval between backflush cycles must be at least long enough as to permit every filter to be backflushed, plus allowing for any abnormally high contaminant loading. There is also an actual dirt-holding capacity for the particular liquid/contaminant combination. In addition, there is also a backflushing efficiency involved, which is a function of the liquid/contaminant combination, the backflush flow rate and other factors. These parameters all combine to give an expression for estimating the filter area:

$$\text{area} = (\text{w.t.ppm})/\text{DHC.BF}.10^6$$

where w = process flow rate in kg/hr; t = backflush interval in hr; ppm = contaminant loading in ppm; DHC = actual dirt-holding capacity in kg/m^2; BF = backflushing efficiency.

This relationship then gives the area required in terms of the number of square metres required for one hour of operation.

The area that is determined in this way is only an estimate since some of the parameters used in the above equation are also estimates (dirt-holding capacity and backflushing efficiency). The main ramification of this is that the backflush interval achieved will be different to some degree from that calculated. In some cases, it is worthwhile to refine the basic data used in the equation by recognizing that the actual dirt-holding capacity is usually affected by the forward flow rate, and that the backflush interval can be corrected to account for the on-stream exposure of most filters during a backflush cleaning cycle.

Where a combination of liquid and gas is used to backflush, a blast of gas is introduced to dislodge the contaminant and then a liquid stream is used to flush the contaminant out of the system. When this approach is used, some relief may be obtained in the reverse pressure and flow requirements for satisfactory cleaning. There is no simple formula that can then be used to optimize the system, primarily because the particular installation frequently imposes design restraints unique to that installation.

A backflushable cartridge system must be sized taking into account both pressure and contaminant loading limitations. Basically the pressure considerations involve ensuring that the system has enough reverse pressure to adequately clean itself and that the system will operate effectively within the pressure constraints of the installation. The reverse pressure drop across the filter medium should be at least equal to, or as much as twice, the maximum forward pressure drop. This requirement usually causes the most concern in an internal backflush system, because the process outlet pressure, which is also the backflush fluid inlet pressure, is lowest when backflush cleaning has to be initiated. In addition, it is usually true of any multi-vessel backflushed system that the forward pressure drop increases to a maximum when the first vessel is taken off stream.

The backwashing process can quite easily be automated, by means of electro-pneumatically operated control valves managed by a dedicated programmed logic controller. Any reasonable backflush interval can be set into the system, and can then be adjusted in the light of operating experience.

Self-cleaning filters

A small but important group of what are, in effect, single cartridge filters are operated in such a way that they can be continuously cleaned by an automatically functioning mechanism. These are called self-cleaning filters (and in some industries, automatic filters – although a wide range of filter types can be arranged to operate automatically).

Basically, the self-cleaning filter is a cartridge element mounted vertically in a housing that contains the cleaning mechanism. This mechanism moves across the outer (upstream) face of the element, cleaning a small area as it moves, and its movement is such as to cover the whole of the filtration area of the element in one cycle, before it returns to its starting position. It may then repeat the cleaning process immediately, or pause for a while before doing so.

The cleaning mechanisms used for this purpose consist of a reverse jet of filtrate coming from inside the element, or a jet or spray playing on the filtration surface, or, most commonly, a brush or scraper moving over the outside of the element (where the solids are collected) to brush or scrape the solids away from the filter surface, to fall into the base of the housing, from which they are periodically removed. (Less often, the cleaning device is kept stationary and the cartridge element is rotated against the brushes or scrapers to remove the collected dirt.) The brushes or scrapers may move around the cartridge, or up and down parallel to the axis of the element.

A very different type of self-cleaning filter is the Fibrotex element, developed by Kalsep, illustrated in Figure 3.60. The element is a bunch of fibres, which acts as a

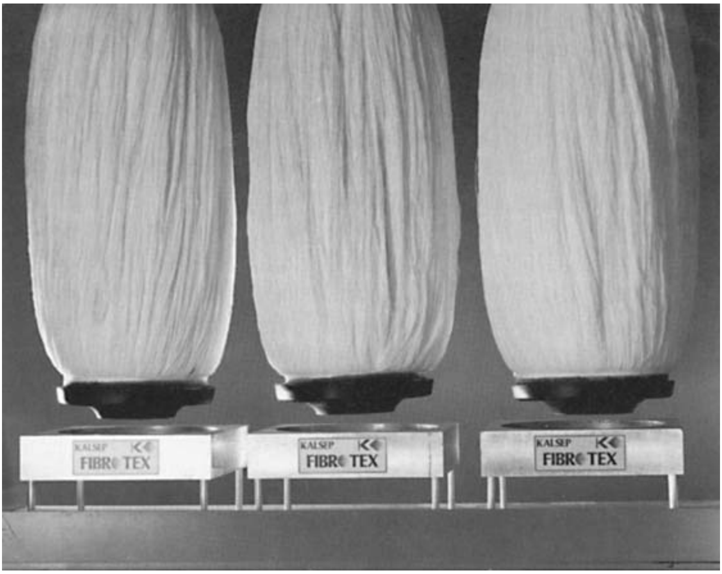


Figure 3.60 Fibrotex elements

depth filter when the bunch is twisted together. When full, the bunch is untwisted, loosening the spaces among the fibres, and allowing collected contaminants to be blown free and discharged.

3N. LEAF AND PLATE FILTERS

The last few parts of this Section (3J to 3M) have been concerned almost entirely with the clarification of a flow of fluid, usually to remove contaminants from it, and very often in a utility function. Most of the remaining parts are now concerned with process filtration, in which the filtration process is intended to recover valuable solids from suspension in a liquid.

Leaf and plate filters are mostly relatively simple pressure-driven filters made up of flat filtration elements, although they can also be vacuum driven. The overall configuration of the filter may be horizontal or vertical, and the basic choice between them is often made according to the space available in the factory. They are mainly used for batch-operated solids recovery, although in combination with precoat they can also be employed for clarification and decontamination duties.

In leaf filters, the elements hang from a manifold at their top, are square, rectangular or circular in shape, and have filter media on both sides. Plate filters have their array of, usually circular, elements mounted one above the other on a central support, and usually filter only on the top surface. Some different leaf and plate elements are illustrated in Figure 3.61. Some care is necessary over the use of words to describe the orientation of the elements in these filters. In this book, horizontal plate

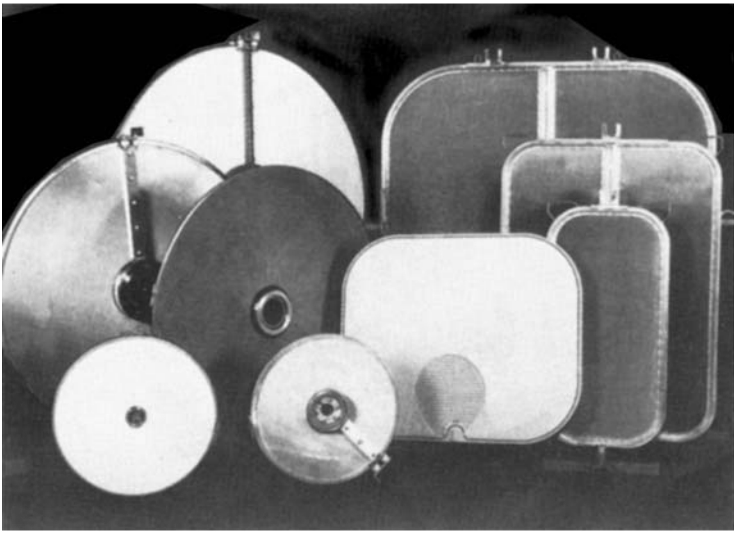


Figure 3.61 Leaf and plate filter elements

filters have the plates mounted on a vertical support, but the plates are horizontal around it (and the pressure shell containing the array of elements is also a vertical cylinder). Leaf filters are vertical element filters, mounted on a horizontal support in a horizontally oriented pressure vessel.

Leaf filters

The leaf filter incorporates an array of flat filter elements, with filter media on both sides of the element, each one parallel to its neighbours and hanging, equally spaced, from a horizontal support that is also the filtrate offtake pipe. The array is enclosed in a pressure vessel, usually circular in cross-section, and there is often one hinged or removable end to this vessel, which may be opened and the array of leaves pulled out for cleaning, as in Figure 3.62. Liquid flows into the shell of the enclosing vessel, through the medium on the leaf to the top of the interior of the leaf, and out into the filtrate collection manifold.

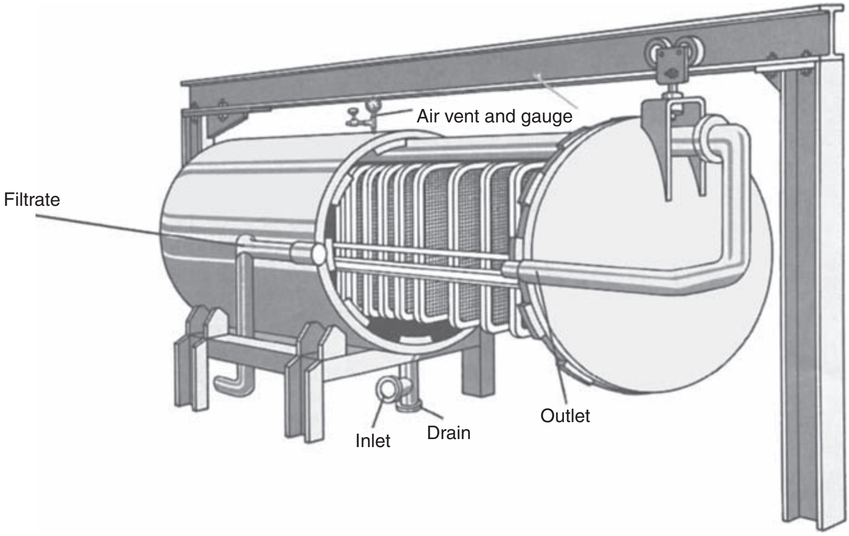


Figure 3.62 Vertical leaf pressure filter

The filter medium is usually a sheet of wire mesh, although finer media are also used, supported on a coarse wire mesh or similarly strong substrate. The filter cake builds up on the surface of the leaves to its optimum thickness (determined not only by feed pressure differential increase, but also by the spacing between the leaves and by the tendency of formed cake to break away from the leaf). The array of leaves is usually stationary during filtration, but may have the capability of being shaken or vibrated to promote cake release. As the batch of suspension comes to an end, the shell is blown free of liquid before the cake is discharged.

An alternative arrangement of vertical leaf pressure filter has the leaves supported on the filtrate manifold from below, with the whole enclosed in a vertical cylindrical shell, as shown in Figure 3.63. The leaves are now of different widths, according to the chord of the cross-sectional circle that they occupy. This version of the vertical leaf pressure filter is the least expensive of the pressure leaf and plate filters.

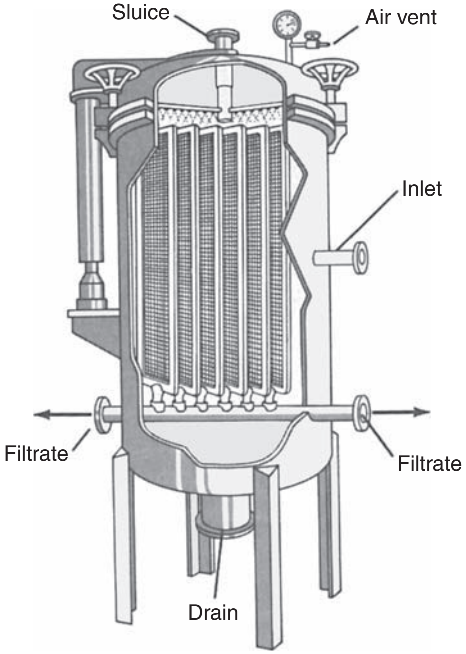


Figure 3.63 Vertical vessel leaf filter

All versions are normally available with wet (i.e. re-slurried) or dry cake. Wet discharge is achieved by the washing of the cake off the leaves, using sprays or a sluice. The sluice may oscillate to ensure that the cake is washed from the whole of the leaf surface. The washing action resuspends the solids in a slurry (usually thicker than the original feed suspension), which is then drained or pumped out of the containing vessel.

Dry discharge can only occur after all of the feed suspension has passed through the filter (with the help of a scavenger plate close to the bottom of the shell if necessary). An air blow may be used to dewater the cake, and a reverse blow to discharge the cake. The leaves may alternatively be freed of cake by use of scraper blades, or be subject to vibration to shake the solids free. However it is done, the cake falls to a conveyor below the filter (usually through doors in the shell) or below the leaf array if it has been removed from the shell as in the filter in Figure 3.62.

Vacuum leaf filters are less common, although cheaper than the pressurized version, because of the lack of a pressure vessel. They consist of an open tank full of the liquid to be filtered, into which the array of vertical leaves is submerged. Vacuum is applied through the filtrate manifold, and cake builds up on the leaves until cake removal becomes due. This kind of filter is mostly used with precoat as a clarifying filter, which is not only cheaper but also more easily inspected and maintained.

Plate filters

The leaves in a pressure leaf filter hang, or are held, vertically and, while this permits filtration on both sides of the leaf, it also means that the accumulating cake can easily fall off the leaf for lack of support below the cake. This problem is overcome by mounting the filter elements horizontally, when they are normally called plates, with filtration occurring on the upper surface only. More often than not, the plates are circular, and they are supported, equi-spaced, on a central post that acts as the filtrate off-take from below the filter medium on each plate, as illustrated in Figure 3.64. This whole array then is housed in a vertical cylindrical pressure vessel. Suspension is fed into the pressure housing, and filtrate flow is through the plate and out through the central pipe.

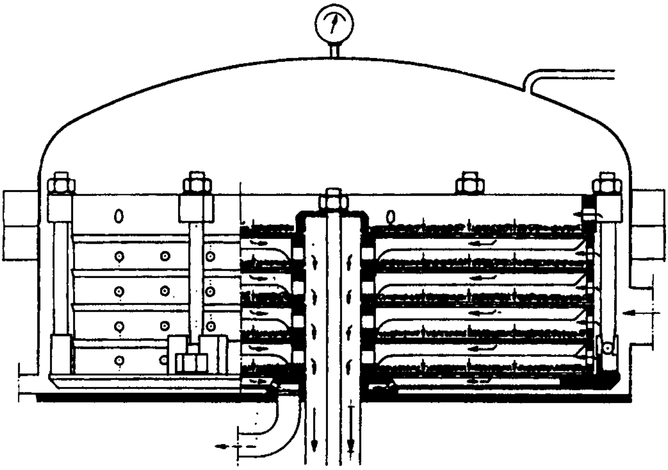


Figure 3.64 Horizontal plate pressure filter

As with leaf filters, the pressure plate filter is operated batch-wise, with a given quantity of suspension fed into the filter, until the design thickness of cake is formed. The main filtration is then stopped and the residual vessel contents are filtered through the plate array. A heel of suspension is left below the bottom plate and this is filtered separately through a scavenger plate that hugs the bottom of the vessel as closely as possible (Figure 3.65). This plate remains closed during the main filtration part of the cycle. At the end of the filtration, the main outlet is closed, and the residual suspension is forced out through the scavenger plate, leaving virtually no unfiltered liquid.

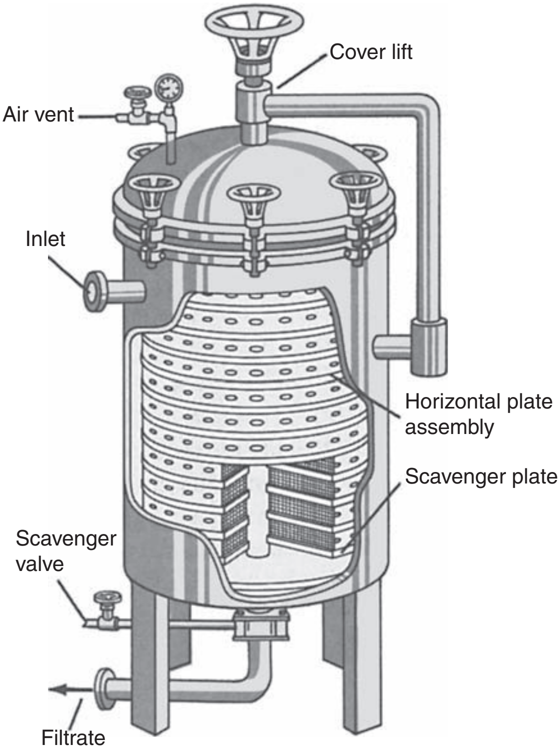


Figure 3.65 Horizontal plate filter with scavenger plate

A filter that combines features of leaf and plate is the dual disc plate filter illustrated in Figure 3.66. The filter elements are now two-sided, filtering on top and bottom (with a single disc at the base of the vessel to act as scavenger). This gives a large filtration area in a smaller floor area, but, of course, suffers from an unsupported cake on the underside of each element. To some extent, this problem is self-correcting since, if cake falls off the underside, the flow resistance decreases at that point, so more filtrate flows through it and the cake is redeposited. This type of filter is mainly used for clarifying and polishing duties.

Cake discharge

The very feature that distinguished the plate filter, i.e. the formation of a cake on the upper surface of the element only, makes this type that much more difficult to operate when it comes to dry cake removal. Wet discharge is as easy as with a leaf

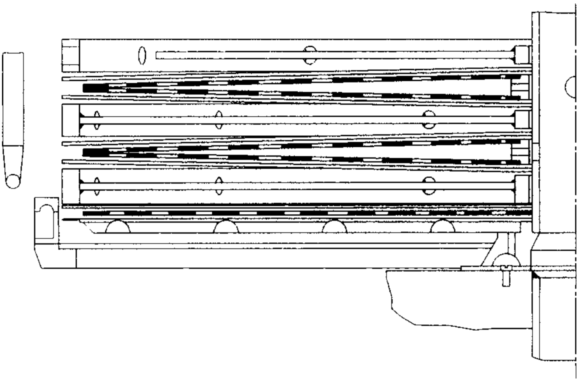


Figure 3.66 Dual disc plate filter

filter, provided that the sluicing reaches every part of the plate. It is less easy, however, once the cake is dry. A set of scrapers can be used, rotating across the surface of a fixed plate (or the plates can be turned under the scrapers).

A novel form of plate filter uses centrifugal motion to clear the plates of accumulated cake. This design (Figure 3.67) has its array of plates now supported on a

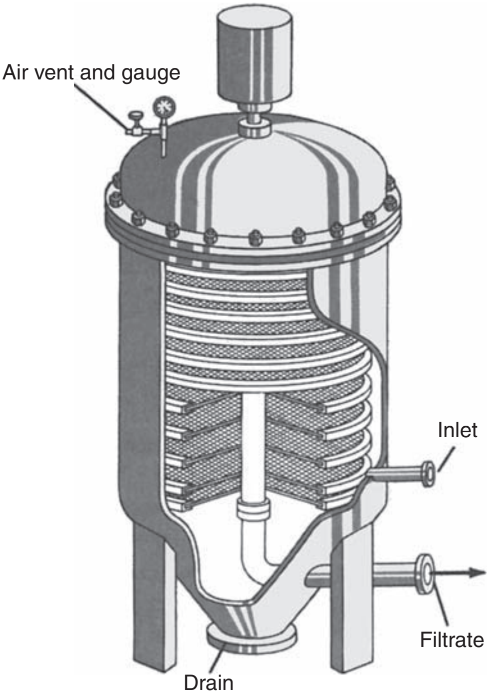


Figure 3.67 Centrifugal discharge plate filter

shaft driven by a motor above the filter vessel. This shaft is hollow and also acts as the filtrate removal pipe. Once the filtration stage is complete, the cake is sucked dry and the plates are then spun to throw the cake to the walls of the vessel and so down and out of the filter.

Vibrating disc filter

The vibrating disc filter has its filter elements ranged horizontally in a vertical cylindrical pressure vessel. This vessel has a large-angled conical base around a large diameter discharge port (Figure 3.68). This filter is a batch unit suited for generally poorly filterable suspensions with a relatively low content of solid matter, and for clarifying filtration.

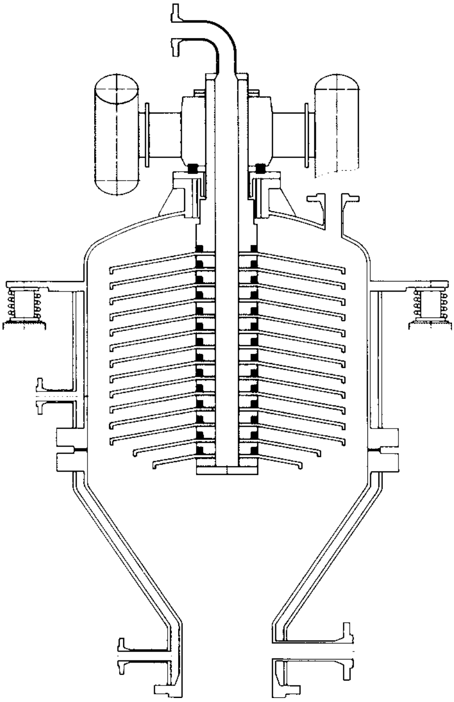


Figure 3.68 Vibrating disc filter

In operation, filtration, and with it cake formation, are done under pressure on the upper side of slightly cone-shaped plates. Two out-of-balance motors cause the plates to gyrate (rotate in a horizontal plane and oscillate vertically). The cake is shaken and pushed outwards, and then falls down into the conical part of the containment vessel for discharge. Typical applications for this filter include adsorption on activated carbon and bleaching earths, separation of catalysts, and upgrading of coal.

Filtration parameters

The leaf and plate filters are batch filters, and a critical element in their selection is the capacity of the filter for the amount of cake to be treated in a single batch. Flow through the filter will depend upon the nature of the suspended solids and their concentration, the liquid viscosity, the pressure available, and a number of other variables. The acceptable value for the flow rate through the filter medium will normally be measured in a test rig. Then the filter can be sized from the calculation of required area:

$$\text{Filtration area} = \text{Required feed rate/Medium filtration rate}$$

A filter with sufficient filtration area to handle the required flow rate or suspension may still fill up with cake too quickly. This may raise the required pressure drop too far or overfill the spaces between neighbouring filter elements. An acceptable cake thickness must be determined by test, whereupon the required filtration area is found from:

$$\text{Filtration area} = \text{Total cake volume per cycle/Maximum cake thickness}$$

The larger of these two measures of filtration area is then the one to be used.

Attractive features of the leaf and plate filters are their ease or operation and maintenance, the large filtration area to vessel volume ratio, the high filtration rates that can be achieved, and their ability to form homogeneous and compact cakes that can be efficiently washed with relatively small wash volumes. There is a minimum number of seals (i.e. potential leak points) between feed and filtrate. Most designs enable filtration, washing, drying and discharging in a closed system.

30. FILTER PRESSES

Although one of the oldest types of filter, the filter press has, over the last century, been the most important of the process pressure filters, and remains important to this day, despite the appearance of competitive types of filter. It has kept this major role by virtue of a small number of design improvements, and also of developments in filter media that have enabled it to keep pace with market demands for improved filtration efficiencies, better energy efficiency, higher degrees of clarity in its filtrates and some measure of automation. Almost every type of filter medium, available in sheet form and with the ability to resist the pressure differentials involved in the filter press, can be used, although membrane media are not often called for outside the microfiltration range.

The filter press has been very successfully applied to the dewatering of a range of sludges, especially those from water and waste treatment processes, and competes strongly in this application with the vacuum belt filter and the decanter centrifuge.

It is not suited to the clarification of liquids, its main purpose being the separation of quite concentrated suspensions, which permit the rapid formation of a cake of separated solids.

It is a batch-operating filter, with filtration cycle times optimized to achieve maximum throughput. A key to such maximization may lie in the ease with which dewatered filter cakes can be removed from the filter's compartments, a feature which can limit the degree to which filter press operation can be automated. The right choice of filter medium goes a long way to facilitating cake discharge.

Plate and frame press

Even in its most highly automated form the filter press is a relatively simple machine, comprising a series of flat filter chambers mounted vertically one beside the other, between two end plates, one fixed and the other movable horizontally, so as to close the plates together. In the earliest form of filter press, the chamber was created by means of two components: a basically flat plate carrying the filter medium and a spacer frame in the form of a wall around the outside of the chamber, which created the space in which the separated solids could collect.

The surface of the flush plate was machined or moulded to provide flow channels for filtrate liquid to run across this surface to the filtrate discharge point(s). A sheet of appropriate filter medium would be placed across the face of the plate, to be supported by the edges of the plate and by the shoulders of the flow channels in it. The frame would then be clamped to the plate, with its sheet of medium, by an identical plate on the other side of the frame. The plates would be double sided, so that each plate could be part of two successive chambers.

This pattern of plate/medium-frame-medium/plate/medium-frame would be repeated along the filter until sufficient filtration area had been built into the system, and the filter would then be closed by bringing up the queen (movable end) plate, carrying a sheet of medium, to be clamped against the last frame of the series. This whole array would then be pressed hard up against the fixed king plate at the other end of the filter (also carrying a sheet of filter medium), to create the whole filter press, formally termed a plate and frame (filter) press.

The plates and frames were suspended by lugs fitted integrally as part of the top of each, from overhead suspension beams, running usually on roller bearings. Alternatively, the plates and frames had lugs protruding from their sides that ran on support bars along each side of the filter press (as in Figure 3.69). The plates and frames were closed up together, along the support bars, between the two end plates, and held close enough together to provide seals between adjacent components of the filter press. The closure of the plates was effected by a hydraulic ram, or mechanically, or by electrically powered screws. Once the filtration cycle was complete, the clamping pressure was relaxed and the plates and frames were moved back along the support beams, to allow the filter cake to be removed from each chamber – which would normally have been done one chamber at a time.

As each plate had a sheet of suitable filter medium fitted over its face, so the spacer frame had filter media on either side of it. The plates, frames and media

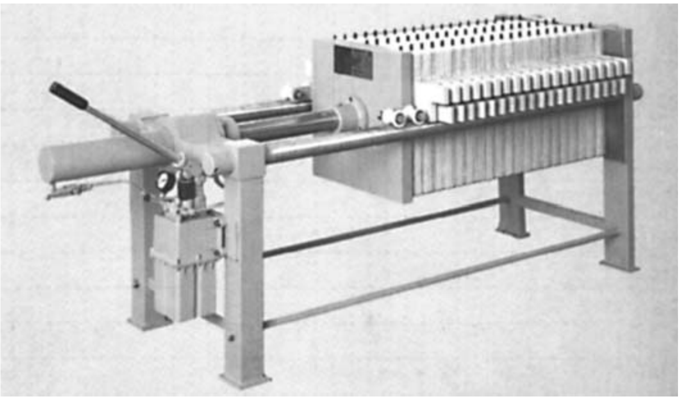


Figure 3.69 Plate and frame press with side bars

sheets all had sets of matching holes in them so that when the filter was closed, flow channels were created along the length of the filter (provided that the sheet of filter medium was accurately placed on the frame). The slurry to be filtered was then fed to the filter through appropriate ports in the fixed king plate, and flowed along corresponding channels through every plate in the array. As it passed each spacer frame it entered the chamber and filled it with slurry. The fluid pressure in the slurry caused filtrate to flow through the filter medium into the drainage channels on the face of the plate, then along these channels to the filtrate exit port, which was usually at the bottom of the plate. The solids left behind accumulated in the cake space and gradually filled it, starting at the surface of the filter medium, and growing in thickness towards the centre of the chamber.

When the cake space was nearly full, the delivery pressure of the slurry would start to rise (or the filtrate rate to fall), giving the signal to stop filtration. If the cake was to be washed, then wash liquor could be introduced from the same channel as the feed (simple washing), and could then be discharged with the filtrate or separately. Alternatively, special wash ports may have been used, to give flow across the thickness of the cake (through washing).

With the cake washed and adequately drained (using compressed air as necessary to remove the last traces of liquid), the filter press would be opened from the queen plate inwards, and the cake in each compartment be discharged into a collection trough or screw conveyor below the filter. Once every cake was discharged, and the filter media washed, then the filter would be closed and the cycle repeated.

Plate and frame presses (and the other types of filter press described below) are made with every conceivable combination of inlet and outlet position. The filters are often used with precoat, when bottom inlet and top outlet positions are considered best.

Recessed plate press

The first main development from the basic plate and frame structure saw the alternating plate and frame replaced by a single set of plates, each two sided, with a raised collar around its periphery, called a recessed plate. Now, when adjacent plates are closed up together, a chamber is formed from the two facing recesses to create the recessed plate press (also called the chamber press), a major part of the filter press market, having largely replaced the plate and frame press, not least because higher filtration pressures are possible with the recessed plate press.

The sheets of filter media are fixed to the faces of the plates, so that when they are closed up, the pieces of medium butt up to one another (Figure 3.70). Now the slurry is fed into the small gap between the sheets of medium, and filtrate flows through the media into the recesses behind them, through the drainage spaces on the surface of the plates, and away to the filtrate discharge port. The filtered solids are left in the space between the sheets of filter media, which slowly expands, under the fluid pressure and as it fills with cake, into the recesses on either side, until the media sit on the raised parts of the plates. The resultant stretching and relaxing of the filter media during each cycle of filtration gives a shorter medium life for the recessed plate filter, to offset against its simpler design and lower first cost.

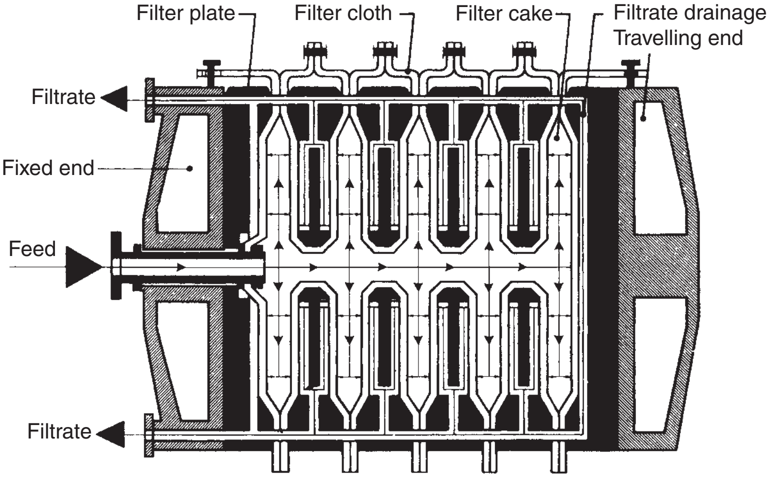


Figure 3.70 Recessed plate press

Operation of the recessed plate filter is much the same as that described above for the plate and frame filter. Some degree of mechanization of the solid discharge process has been achieved, leading to a measure of automation in the operation of a recessed plate filter press.

Working pressures for filter presses are upwards of 7 bar. Plates, originally of wood, are now made from a variety of materials, including rubber-lined steel and moulded plastic. They are available in a range of sizes, from 15 cm square, up to 2 m square, and they are installed up to 100 or more in one filter press.

The plates are normally square in shape, with delivery and offtake ports in the centre, and/or at the corners (Figure 3.71). This gives the chance to have the feed

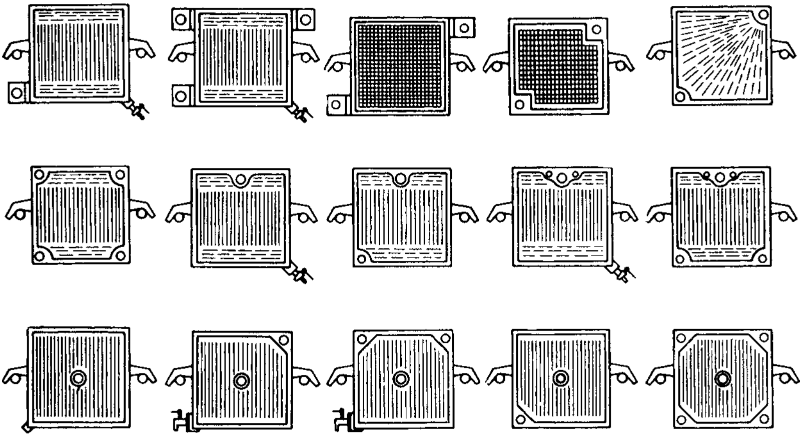


Figure 3.71 Filter press plate forms

point at the centre or at the top, as well as at the base – from which the slurry will rise to fill each compartment (there usually being some problems with cake distribution across the area of the plate). Feed from two points is also possible to alleviate the distribution problem.

Not only does the filter medium act in its separative function, but it also provides the seal between plates – not just at the outer edges, but also around every port. The sheets of media must therefore be made to quite strict tolerances, from material that will not change in shape with continued use. Nevertheless, leakage from the joints is a common problem with the filter press, because the material forming the sealing gasket is part of the filter medium, and therefore intrinsically porous – a problem that can be solved by using filter media that have been coated with elastomeric materials around the required sealing areas.

It is possible that the filtration cycle should be stopped short of maximum cake thickness, since the pressure starts to increase well before that point, and filtrate rate may fall to an unacceptable level. The question of optimum cake thickness is an important parameter in filter press design. The plate and frame and recessed plate presses do not allow much freedom to vary cake thickness, very much decided by the width of the recess, should a very dry cake be required.

Diaphragm filter press

The main development of the filter press from the simpler versions just described has been to include an impervious elastomeric sheet in each plate compartment (one for each plate on the feed side of the filter medium, butting up against the corresponding sheet of the next plate). These flexible sheets can be inflated pneumatically so as to press down on the drained cake, once filtration is complete, and so dewater it by compression. This type of filter press is then known as the diaphragm filter press (as shown in Figure 3.72). (Initially this sheet was referred to as a membrane, and the term 'membrane filter press' became quite confusingly well-known.

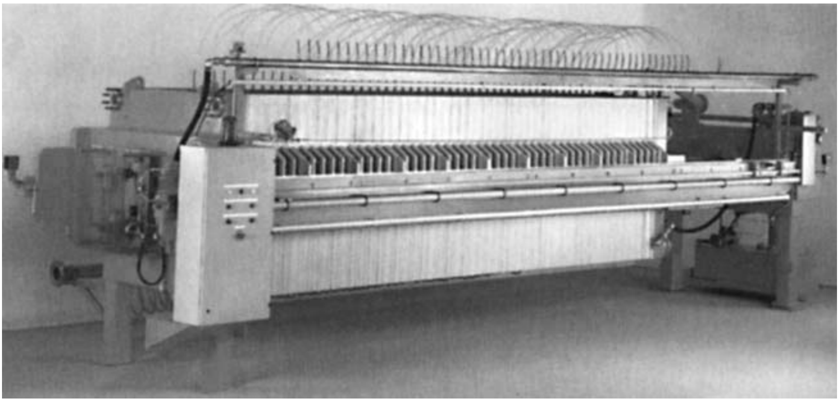


Figure 3.72 Diaphragm press

The alternative meaning of membrane as a semi-permeable material required the change to the use of the word diaphragm.)

The filtration cycle can be shortened in the diaphragm press while still producing a dry cake. This enables the optimization of the cycle time, to maximize output: although the volume of cake produced per cycle may be less, the number of cycles per unit time can more than compensate for this.

The filter cake is formed at pressures up to around 8 bar, but then the diaphragm exerts a pressure of up to 15 bar or more to dewater the cake, enabling capacity increases of 50% on a corresponding recessed plate press.

Vertical filter presses

The great success of the filter press has led to several other designs of filter employing the plate principle, most notably the vertical filter press (or tower press as this type is sometimes called – but so is a type of belt press, discussed in Section 3P), which is basically a filter press stood on one end with a continuous band of filter medium passing progressively over each plate in turn. This arrangement can add gravity to the hydraulic head as a driving force, and also means that the cakes form evenly without the slippage cracks occurring in the horizontal filter. Washing can thus be uniform as well.

The vertical filter press, like the horizontal press, is strictly speaking a batch operating filter, but is more correctly called a semi-continuous filter, because the cake is discharged from all of the compartments at the same time. When the filtration cycle starts, the plate assembly (Figure 3.73) closes, and slurry is fed to all of the compartments at the same time. Cakes form on top of the filter medium in each compartment. Once filtration is complete, diaphragms are forced hydraulically down on the cakes to dewater them. Then the diaphragms are relaxed, wash water is introduced, and the cakes squeezed once again, followed by a compressed air blast to dry them further. At this point, the plate assembly opens, and the continuous band of filter medium advances

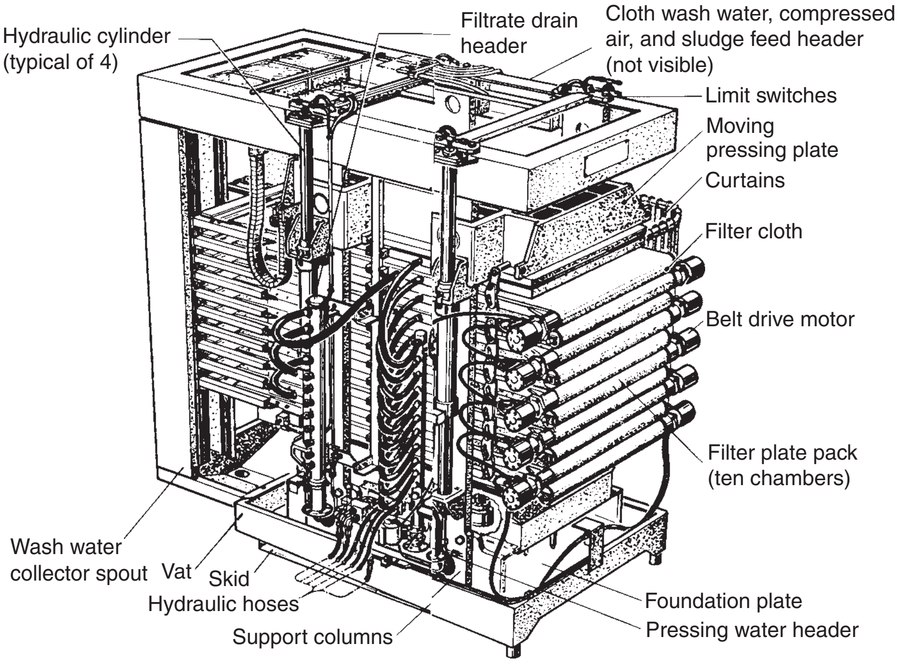


Figure 3.73 Vertical filter press

one compartment's length throughout the whole filter. As it does so, it passes over small diameter rollers at each end of the compartment, breaking away the cakes, which fall into collection troughs below the filter. The filter medium is now reversed (the bottom side is now facing upwards and vice versa), so it is washed, and the process repeated.

The vertical filter press is a very effective unit, fully automatic in operation, though somewhat expensive. It occupies less floor space than a horizontal filter press of the same filtration area.

3P. BELT PRESSES

Belt presses (or press belts or double belt presses as they are equally usefully known), as their name implies, use the pressure of a belt on a mass of wet solids to dewater the solids. They are not filters, because they work by squeezing liquid out of a sludge, but they can be important adjuncts to filters. They work by accepting a reasonably stiff feed suspension onto a continuous lower belt, which carries the wet mass under an upper belt that is pressed down on to the lower one by a series of rollers.

Small belt presses can be used as the final dewatering stage on a vacuum belt filter, or even on a rotary drum filter. When added to a belt filter (as in Figure 3.74), the vacuum dewatered cake is taken by the belt around a series of rollers and squeezed between a subsiding belt acting on top of the cake and a series of taut narrow belts acting on the underside of the main belt, with gaps between them for the liquid to

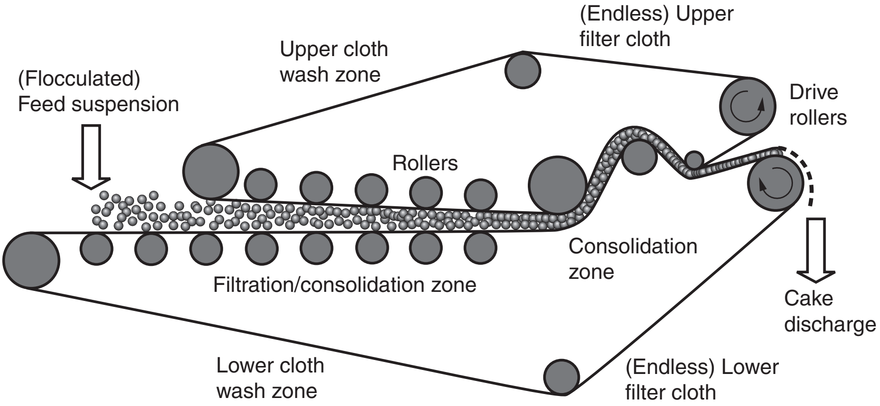


Figure 3.74 Vacuum belt filter with auxiliary belt press

pass through. The distance between the upper and lower rollers reduces, causing pressure to build up gradually in the cake as it passes over the rollers. The belts move slightly in relation to one another as they pass through the sets of rollers, thus shearing the cake and releasing more filtrate.

The double belt press is similar in layout to the filter shown in Figure 3.74, except that the lower belt is impervious. Once the dewatering sludge is caught up between the belts, there is no reason for the belts to be horizontal, so they can be mounted vertically as in the Manor tower press.

3Q. VARIABLE VOLUME FILTERS

A small group of filters is classed together as variable volume devices, so called because the filtration zone containing the collected solids is compressed once filtration is complete, in order to dewater the filter cake further before discharge. The diaphragm filter press, described in the previous chapter, fits that definition, but is more sensibly included as a variant of the horizontal filter presses, leaving two other closely related designs.

The first, known as the variable chamber (or VC) filter, was developed in the dyestuffs industry, in order to produce dyes with the maximum of mechanical dewatering ahead of drying. It is illustrated in Figure 3.75. It consists of two concentric hollow cylinders, the filter medium being secured around the perforated inner cylinder, while the outer cylinder is lined with a rubber diaphragm. In operation, the slurry is fed under pressure into the annulus between the filter cloth and the diaphragm. The feed pressure causes the mother liquor to pass through the medium and leave the filter.

The filtered solids are retained on the filter medium, and at an economic point, determined by volume, flow, time or pressure, the slurry feed is stopped and the cake is compressed by the diaphragm at a pressure of up to 14 bar, removing further liquor and producing a final cake that can contain less than 10% moisture.

A feature of this type of filter press is its ability to stop filtration at varying cake thicknesses. The filter is not continuous in the strict sense, since the inner cylinder

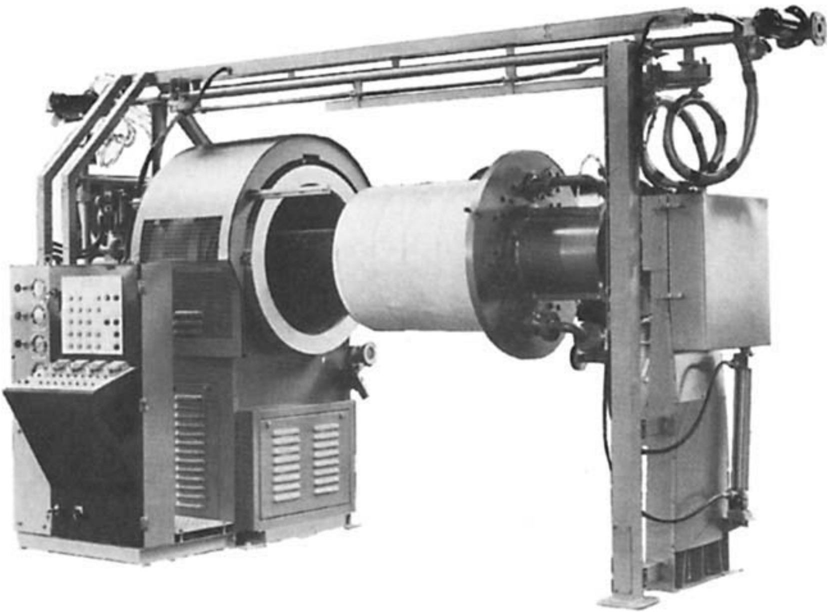


Figure 3.75 Variable chamber filter

must be withdrawn in order to discharge the cake, although the turnaround period is only a matter of minutes.

The second design of variable volume pressure filter is the tube press, developed by English China Clays, for the filtration and dewatering of kaolin suspensions. It is a batch operating filter, whose principle is much the same as in the VC filter, except that the axis of the filter unit is vertical rather than horizontal. A vertical cylinder of filter medium is enclosed by a cylindrical elastomeric sleeve, outside which is a cylindrical pressure vessel. The slurry to be filtered is introduced between the filter element and the surrounding sleeve, at relatively low, although increasing, delivery pressures. Filtrate flows through the filter medium and the solids remain as an annular layer of cake between the medium and the diaphragm.

Once the maximum feed pressure has been reached, depending on the nature of the feed pump, then the feed system is closed and the tube press is isolated. Hydraulic fluid is now introduced between the elastomeric sleeve and the pressure vessel outside it, so as to squeeze the filter cake by means of the flexible sleeve. Squeezing pressures up to 140 bar are used, to dewater the filter cake, often to a degree of dryness where further thermal drying is unnecessary. The sleeve is then sucked off the cake by vacuum, and the inner tube is lowered free of its housing, and a pulse of compressed air cracks the cake, which falls off the candle into a receiving vessel below it.

The tube press is available in a small selection of lengths, for a constant diameter, and larger capacities are achieved by employing an array of presses side-by-side, with operations timed in sequence so that delivery of the product cake is continuous.

3R. SCREW PRESSES

A screw press is a continuously operating machine used to squeeze liquid from a mass of fibrous solids, such as in the recovery of animal or vegetable oils, or further to dewater a pasty filter cake. It consists of a screw rotating inside a perforated or slotted shell, so that the mass is pressed against the inside of the shell. The solids must be coarse or stiff enough so that they do not pass through the holes in the shell, while the expressed liquids are extruded through the perforations in the shell and collected in a surrounding casing.

The press can be operated with its axis vertical or horizontal. Pressure is increased along the length of the press either by reducing the screw pitch, or by increasing the shaft diameter or by reducing the diameter of the shell, and can be controlled by varying the size of the outlet for the squeezed solids. The shaft may be hollow to permit steam heating, and wash liquid can be added along the screw to increase recovery.

The expressive forces are high so that screw presses are rugged machines, and the shell can only have fairly coarse perforations. Accordingly, the liquid produced in a screw press will almost certainly need a stage of filtration after the press.

A similar function to that of the screw press, i.e. the expression of liquids contained in natural products, can be achieved by means of rollers, or vertically mounted discs (rotating on axes slightly inclined down from the horizontal so that there is a pinch zone at the bottom of the rotation) – but neither is a filtration process.

3S. CROSS-FLOW AND MEMBRANE SYSTEMS

There are two distinct modes of liquid filtration. In one, the filter medium sits across the fluid flow channel, so that all of the liquid must pass through the medium, leaving any separated solids to be held in or on the medium. This is called through-flow or dead-end filtration, and it separates most or all of the suspended solids from a more or less completely clarified liquid.

In the other mode, the flow of suspension is parallel to the medium, and some of the liquid flows through the medium by virtue of there being a pressure difference across it. The remainder of the slurry flows on and out of the filter. Very little of the suspended solid remains on the medium, and the intention is that the flow of liquid across the surface of the medium should indeed keep it scoured free of any deposit. This is called cross-flow filtration (sometimes tangential-flow), and while it can give extremely clear filtrates (in this context usually called permeates), it is only a thickener as far as the slurry is concerned.

Cross-flow filtration normally employs a surface filtration medium, since any solids moving into the thickness of the medium would not improve the efficiency of the process, and would reduce the active life of the filter medium. This medium is usually (but not always) a membrane, which is why the two topics are covered in this one chapter. (There is also considerable coverage of the membrane and related filters in Section 2F.)

Cross-flow filtration

The cross-flow principle (Figure 3.76) began with the hollow fibres used in reverse osmosis, and has expanded to become one of the most important components of the filtration industry. In order to keep the surface free of deposit, high-shear conditions are employed, and these can be created either by a high suspension velocity across the medium, or by some sort of movement (rotation, vibration, etc.) of the medium with respect to the liquid flow or a nearby non-porous surface. This latter group, of movement promoted filtration, is often termed dynamic cross-flow filter systems.

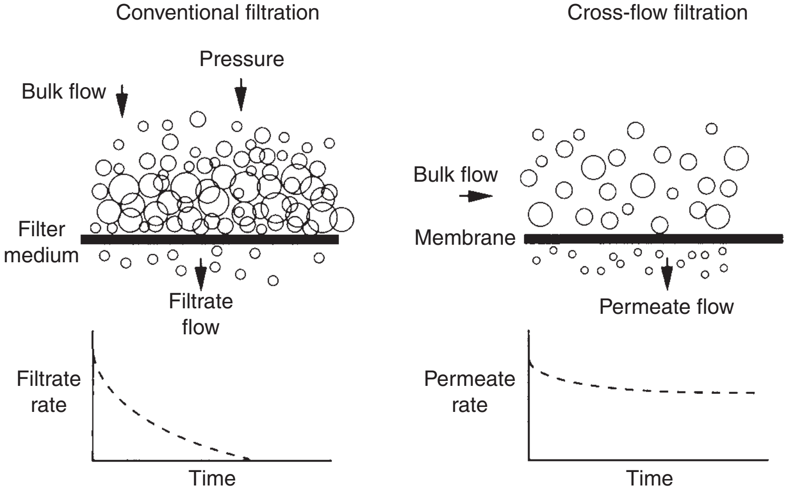


Figure 3.76 Cross-flow filtration

Cross-flow filtration can be classed as one of a number of thin layer filter systems. It is one of the three main practical filtration processes (the others being cake filtration and depth filtration, with surface straining being a less-used fourth process).

The dynamic cross-flow filters address the problem of the reduction of flow through the filter medium (filtrate flux), which is caused either by fouling of the membrane surface and consequent blockage of the pores in the membrane, or by the increase in concentration of the particles or large molecules as they approach the membrane, but are not being allowed through it. The fouling and increased concentration will both restrict passage of the liquid to and through the membrane. The dynamic systems reduce the impact of fouling or concentration polarization by agitating the zone close to the membrane surface in some way so as to create additional shear in it.

The VSEP (Vibratory Shear Enhanced Processing) system made by New Logic Research is an example of the vibration technique. It uses a stack of circular membrane discs, each with membrane media on both sides, enclosed in a relatively small housing (over 100 m^2 of membrane area in less than 200 litres of housing volume). The stack is then vibrated torsionally, i.e. in a direction parallel to the discs.

A similar stack of discs may be rotated about the central axis to give rotational promotion of shear, but this arrangement is improved if a stationary non-porous disc is mounted between each pair of membrane discs. The opposite arrangement with stationary membrane discs and rotating non-porous discs is equally effective.

Membrane filters

Originally implying a thin, microporous or semi-permeable plastic sheet, the term ‘membrane’ is now applied to any filter medium that is capable of removing particles below 0.1 μm. The membrane represents probably the fastest growing part of the filtration media market (especially if ceramic membranes for hot gas filtration are included).

Modern membrane technology began with the development of the first high performance membrane for the desalination of salt water by reverse osmosis, as reported in Loeb and Sourirajan’s seminal paper of 1963. From these beginnings as a thin, flexible semi-permeable sheet of regenerated cellulose material, developed to separate species at the molecular and ionic level, the membrane has expanded enormously, to embrace solid inflexible ceramic and sintered metal, and an ever-increasing group of polymeric materials, and to applications that now extend well into the microfiltration range. The existence of the membrane as a very effective filtration medium led to the development of the whole field of cross-flow filtration, described above, which also now extends well beyond its reverse osmosis origins.

To many people, a membrane remains a thin flexible material, but in filtration terms the word now covers any medium that can achieve separations at 0.1 μm or below (down to molecular and ionic sizes), and which may be thick or thin, flexible or rigid, organic or inorganic. In addition, many membranes are now employed in microfiltration applications at cut sizes well above 0.1 μm.

The membrane is essentially a surface filtration device, with depth filtration intentionally not involved in its use. In practice many membranes are of asymmetric structure and effectively comprise two layers. The active, surface layer is a very thin skin, the permeability of which is of critical importance. The lower, thicker layer is of more open structure, its role being to serve as a mechanical support for the active layer.

The irregularity of the pores of most membranes, and the often irregular shape of the particles being filtered, results in there not being a sharp cut-off size during filtration. With symmetric membranes some degree of depth filtration could occur as smaller particles move through the tortuous flow path. To counteract this effect, asymmetric membranes, which have surface pore sizes much less than those in the bulk of the membrane material, are used to trap the particles almost exclusively at one surface (the membrane skin) whilst still offering low hydrodynamic resistance.

The fine surface structure of all membranes implies the need for significant pressure drops across the medium in order to achieve adequate fluid fluxes. As a result, membranes need to be contained in pressure tight housings, and considerable ingenuity is required to achieve sound and efficient operation.

The main processes in which membranes are used in industry are the:

- filtration of fine particles, down to less than 0.1 μm in effective diameter, from suspension in liquids or gases (microfiltration)
- removal of very large molecules and colloidal substances from liquids (ultrafiltration)
- selective removal of some ionic species from solution (nanofiltration)
- removal of effectively all dissolved and suspended matter from water and other solvents (reverse osmosis)
- selective transport of ionic species only (electrodialysis)
- separation of mixtures of miscible liquids (pervaporation), and
- separation of gas mixtures, including mixtures of gases and vapours (gas and vapour permeation).

Most membrane processes operate by means of cross-flow filtration, in which only part of the fluid passes through the membrane as filtrate (or, more correctly, permeate, since some membrane processes operate by permeation rather than filtration); the retained part, the concentrate or retentate, consequently becomes more concentrated in particulate or solute species. Membrane systems are frequently operated in a closed loop, with the retentate recycled, and final concentrate is taken from the loop in proportion to the added feed suspension. Whereas microfiltration utilizes both through-flow and cross-flow filtration, cross-flow is the usual mode for the other membrane filtration processes, and has thereby grown to its present level of importance.

Depending on the properties of the material used, membranes may be produced in the following geometrical forms:

- flat sheets, which are self-supporting or backed by a supporting substrate, and can be paper-like in format and so be pleated and made into cylindrical cartridges
- spiral wound, which is made by laying a series of membrane sheets and spacer sheets alternately, and rolling this array up into a cylinder
- tubes – self-supporting or backed by a supporting substrate, typically 12–24 mm in internal diameter
- perforated blocks, circular or hexagonal in cross-section, perforated parallel to the axis of the block by a set of channels, on the surface of which the membrane is laid (as in Figure 3.77)
- hollow fibres – typically 40 μm internal diameter and 80 μm outside diameter, used in bundles sealed into plates at each end of the module.

These formats are then made up as modules, and enclosed in a suitable cylindrical housing. These modules are very often employed side-by-side in multi-housing arrays to provide adequate filtration area, and these arrays can reach very large sizes (Figure 3.78). Polymeric membranes are used in all these forms except the perforated block, which is very largely restricted to inorganic materials.

Because of the very fine nature of membrane media, it is normal practice to employ a filter, ahead of the membrane unit, which is intended to remove any particulate material that might interfere with the membrane process. This is especially necessary where the flow passages are very narrow, such as in hollow fibre membranes. In fact, some membranes themselves are used as prefilters to membranes operating at a finer

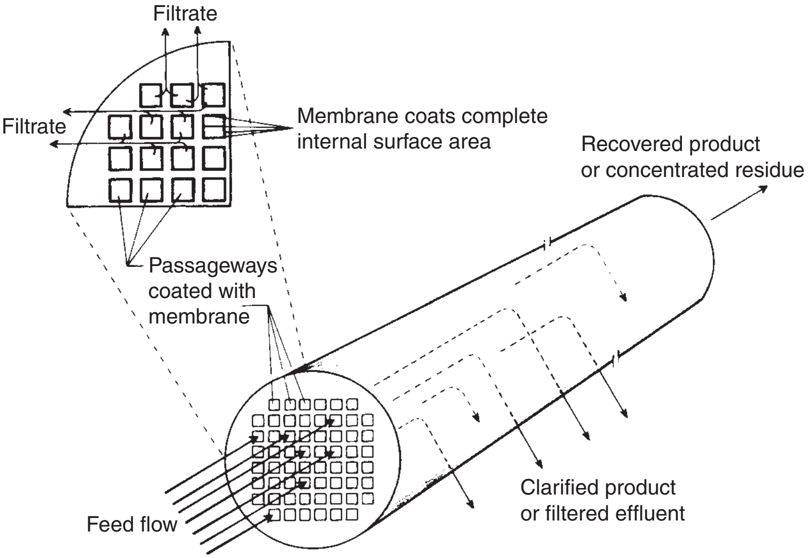


Figure 3.77 Monolithic membrane structure

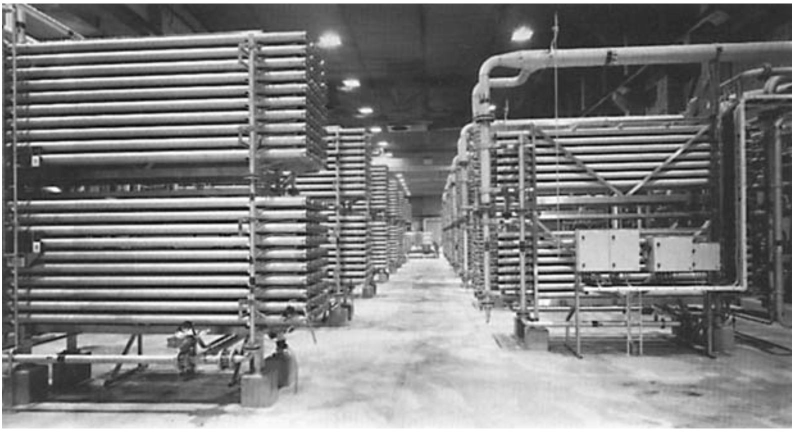


Figure 3.78 Large membrane array

degree of separation. Thus there will normally be a microfilter ahead of an ultrafiltration or reverse osmosis membrane, but there may also be an ultrafiltration membrane ahead of a reverse osmosis step.

Flux reduction

The build-up of a fouling layer on the surface of a membrane is one of the most serious problems in membrane processes. The term 'fouling,' rather than the more familiar 'filter cake,' arose from the origins of membrane processes in molecular separations, where macromolecular proteins would separate on to the membrane surface as a slimy, gel layer, which rapidly reduced the flux through the membrane. Fouling layers have to be removed periodically by cleaning, but much ingenuity is employed by membrane system designers to minimize the formation of a fouling layer in the first place.

The extent to which cross-flow successfully prevents the surface of the membrane being fouled by deposited particles is dependent on a variety of factors, especially the cross-flow velocity. Chemical and/or mechanical procedures are usually required to clean (and sterilize) the membrane, which must be able to withstand the associated mechanical, chemical and thermal stresses.

Another operating problem, concentration polarization, affects the membrane processes dealing with suspended or dissolved species. The molecules to be separated (i.e. kept in the retentate) diffuse through the liquid close to the membrane surface and become much more concentrated at the surface, creating a different kind of barrier to liquid flow, and so reducing flux. In the same way, the particulate matter accumulates in the liquid as it approaches the boundary layer, creating a similar resistance to liquid flow.

As well as local shear, there are two other types of method employed to reduce fouling and/or concentration polarization, and so increase flux rates:

- changes in the surface characteristics of the membrane, and
- conditioning of the feed slurry/solution.

The surface of the membrane needs to be as smooth as possible, and the slurry or solution as free as possible of material that will foul the surface. Operational modifications are generally designed to create some kind of shearing or scouring of the fouling layer. Some of these are mechanical, while the use of a two-phase (gas/liquid) flow is growing in importance.

Membrane manufacture

Factors that have a profound influence on the structure or morphology of a particular membrane are the nature of the process by which it is manufactured and the form of the raw material used. The main manufacturing processes are:

- sintering of fine graded particles
- solvent casting or phase inversion, involving the stage-wise evaporation of a solution of polymer in a mixture of solvents
- irradiation and etching of an impervious film, and
- stretching an impervious film to cause multiple ruptures.

To be effective for separation, membranes should exhibit appropriate characteristics, such as good chemical resistance (to both feed and cleaning fluids), mechanical stability, thermal stability, high permeability, high selectivity and general stability in operation. Originally, all membranes were based on natural materials or derivatives of natural cellulose. Whilst cellulosic media continue to play an important role in certain areas of application, the major source of membranes is now synthetic polymers. There is an immense variety of polymeric materials available as membrane media, including grades with specially developed properties (hydrophobic or hydrophilic, anionic or cationic) for specific filtration applications.

During the last twenty years or so, inorganic materials such as ceramics and metals have become of increasing significance as membrane materials. The introduction of these, despite their being nearly an order of magnitude more expensive than their organic counterparts, has occurred because of their much-improved operating lifetimes, their robustness, their greater tolerance to extreme conditions of operation, such as higher temperature and aggressive chemicals, and the subsequent overall saving in lifetime costs.

Membrane bioreactor (MBR)

A significant development in membrane technology has been the membrane bioreactor. This is a combination of a bioreactor (i.e. a reactor in which a biological process occurs, most commonly the secondary or activated sludge stage of a wastewater treatment system) with a membrane filter, operating in through-flow or crossflow. This has become a major system in the treatment of wastewater.

The MBR takes the place of the settlement stage after secondary treatment, which reduces the organic content of the waste liquor by biological action. The separation is achieved by ultrafiltration membranes, in hollow fibre or sheet formats, submerged in the main secondary treatment vessel, and often with air bubble scouring of the outer surfaces to extend operating times.

3T. MAGNETIC FILTERS

Magnetic filters are specialized straining systems for the removal of iron and other ferro-magnetic particles from liquid suspensions and flows of solid particles. They are in effect simple magnets or magnetic assemblies that, when suitably located in a fluid system, can attract and retain ferrous metal, nickel and cobalt particles that may be present in that system, and also composite particles in which a ferromagnetic material is entrained. Their main uses are for the trapping and retention of ferrous metal machining or wear products in lubrication systems and hydraulic systems (particularly when running-in a new system), removal of ferrous particles from ceramic slip in the pottery industry, removal of ferrous particles from process feed lines and pneumatic conveyors, and the separation and retention of swarf from machine tool coolants.

Elements employed in such cases are invariably permanent magnets. Until the appearance of high energy permanently magnetic materials, the efficiency of magnetic filters was somewhat limited. With modern alloys offering a remanence in excess of 10,000 gauss and a BH_{max} of the order of 4×10^6 gauss-oersteds, the efficiency of a permanent magnet can be extremely high.

In its simplest form, a magnetic filter may be in the form of a plug replacing the conventional drain plug in a crank case, as in Figure 3.79. Ferrous metal particles flowing into the magnetic field generated by the plug are attracted to the plug, where they adhere and remain trapped. The plug can then be cleaned by scraping when it is removed, for example at each oil change. Plugs of this type are particularly useful for trapping initial wear products generated during the running-in period of internal combustion engines, gearboxes, gear pumps and similar machines. A more efficient form of magnetic drain plug, instead of relying purely on magnetic attraction, traps the ferrous contaminants between a number of magnetized rings or magnets encircling the plug core.

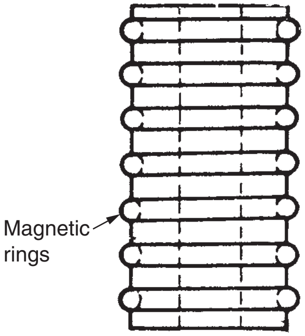


Figure 3.79 Magnetic crankcase drain plug

For other applications the magnetic element can be designed to suit the flow conditions involved. Basically any such assembly of magnets should be designed so that fluid is caused to flow over or through those parts of the elements at which the magnetic field is strongest, and preferably this flow should be free from turbulence.

It is also desirable, whenever possible, to arrange that the majority or all of the particles are retained outside the mainstream flow, so that accumulation of contaminant cannot impede the flow. For maximum efficiency it is further desirable that the direction of flow of the fluid is the same as that of the magnetic field. The particles are then more readily diverted to the magnetic elements and withdrawn from the main flow. The normal arrangement is a series of magnets of cylindrical or quadrant shape retained in position by a non-ferrous metal cage or cylinder, and clamped between two mild steel pole pieces at the top and bottom of the assembly. The external field passes between the pole pieces via a mild steel cage, which has a series of gaps, across which a strong flux is maintained. These gaps provide a concentration of the field and thus ensure a strong field gradient for effective removal of ferrous contaminants. A magnetic assembly of this type is shown in Figure 3.80.

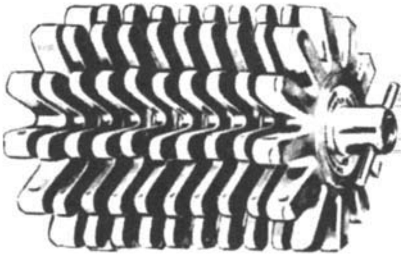


Figure 3.80 Typical magnetic filter assembly

Pipeline filters

Just like the pipeline strainers described in Section 3B, special forms of magnetic filters have been developed specifically for installation in pipelines, an easily cleaned version being illustrated in Figure 3.81. Here, the central core of the filter element comprises a permanent magnet enclosed in a non-magnetic cover. Surrounding this cover are a number of mild steel or iron segments connected by brass strips so as to leave a small gap between each segment in which ferrous contaminant is trapped.

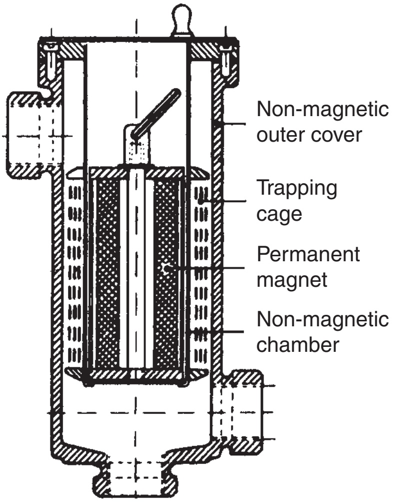


Figure 3.81 Magnetic pipeline filter

The purpose of the non-magnetic cover around the magnet is to ensure that it does not become contaminated with particles. Thus, the majority of the contaminants are collected between the segments, with some on the end pieces. The cages are split for ease of removal, and, once removed from the magnet assembly, are no longer magnetized, so cleaning is simple and straightforward.

Line filters of this type can be made in virtually any size. Standard productions cover flow rates from $0.5\,m^3$/hr or less to $20\,m^3$/hr. In the larger sizes, two or more banks of rings may be provided in the cages to increase the number of air gaps, and thus the particle retention capacity of the filter – otherwise the design follows similar lines.

As an alternative to removing the cages for cleaning, the central magnet itself may be withdrawn to de-energize the cages for flushing clean. To avoid flushing contaminant into the normal outlet, a further port is provided at the bottom of the casing for flushing direct into a separate draining bucket or receptacle.

Trough filters

The design of a permanent magnet filter suitable for use in troughs or settling tanks is shown in Figure 3.82. A number of core magnets are arranged side-by-side in a non-magnetic housing and effectively connected in parallel by the special pole pieces. The filter cage then consists of a series of strips on either side of the magnets, located

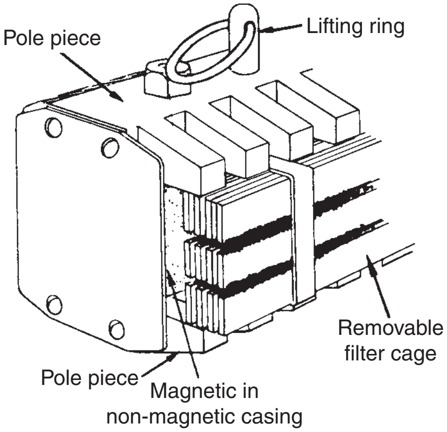


Figure 3.82 Magnetic trough filter components

between the pole pieces. The filter is placed in the trough in the line of flow. A complete assembly is shown in Figure 3.83.

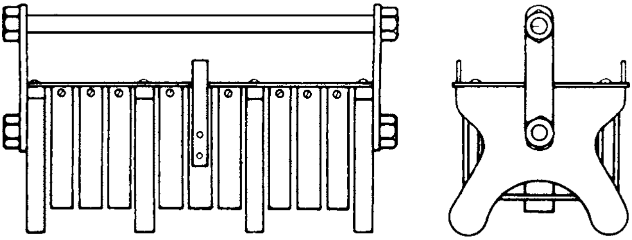


Figure 3.83 Complete trough filter

Magnetic elements may also be fitted into the feed pipes or funnels of troughs, the magnetic filter funnel being widely used in the pottery and paint industries.

Combined magnetic and mechanical filters

In many cases magnetic filter elements may be combined with mechanical filter elements in a single housing to remove both ferrous and non-ferrous contaminants in a single pass through the filter. A typical example of a high duty filter of this type is shown in Figure 3.84. More simply, the same effect may be provided by inserting a magnetic plug in the main flow channel of a standard mechanical filter.

Vibratory magnetic filter

The vibratory filter is a high intensity magnetic filter, specifically used for removing fine iron bearing contaminants from mineral slurries and other fluid media, as well as from free-flowing streams of solid particles. Typical fluid applications include

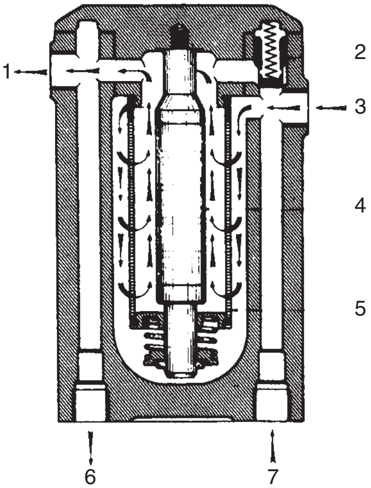


Figure 3.84 High pressure microfilter with magnetic and mechanical elements. 1, Side outlet; 2, relief-valve; 3, side inlet; 4, magnetic filter; 5, replaceable microfilter element; 6, alternative bottom outlet; 7, alternative bottom inlet.

the processing of ceramic slips and glazes, clays, inks and toners, while powders treated include fine sands, glass powders, talc, and silica and zircon flours.

In operation, a solenoid electromagnet generates a magnetic field into the bore of the coil. A filter element of expanded metal placed in the coil concentrates the flux of the magnetic field. This produces a myriad high gradient collection zones that capture magnetic contaminants as the feed material filters through the element. To enhance the fluidity of the very fine powder as it passes through the matrix, the canister is attached to two high-frequency, low-amplitude vibratory drives. When feed materials flow through the magnetized matrix, the iron bearing contaminants are captured and held.

Rotating disc clarifier

Another important application of the magnetic filter is in the use of a rotating magnetic disc as the filter element, particularly for the treatment of machine tool coolants. The disc unit is designed so that it can be mounted at any height alongside a grinding wheel or honing machine. Coolant from the machine tool is fed direct to a clarifying chamber containing the rotating magnetic disc. Ferrous swarf and grindings are removed from the coolant, and then collected off the wheel into swarf containers and withdrawn periodically for emptying.

The entry to the clarifier is a narrow channel into which the coolant leaving the machine is fed under gravity. It then flows past a slowly rotating aluminium disc turning in an opposite direction, inset into the periphery of which are a series of permanent magnets or magnet assemblies. These collect any ferrous contaminants present in the fluid and lift them clear of the tank, where the magnets are scraped clean by wiper blades, sweeping the contaminants into separate containers.

Magnetic separators

Magnetic separators, so called in the industry, are confusingly exactly the same in principle as a magnetic filter or a magnetic clarifier: attracting and retaining ferro-magnetic solids contained in a product being treated. Particular spheres of application are for the removal of harmful metallic particles and sludges from coolants in re-moulding and machine tool systems, and for mineral processing. A magnetic separator is an ideal choice of clarifying system where the use of coolant lubricants depends on clean fluids such as emulsions, aqueous solutions and cutting or grinding oil.

In operation, contaminated working fluid flows through a channel into an inlet box and then into a separating zone, shown diagrammatically in Figure 3.85. A magnetic rotor turns slowly against the direction of the flow. The magnetic field acts on the ferritic contamination along the entire width of the rotor. Ring magnets attract the magnetic particles along with adherent non-magnetic dirt particles, and convey them to a scraper plate mounted at an angle to the magnetic rotor, allowing any residual fluid to flow back into the container. The sludge taken from the rotor builds up on the scraper plate, dries and is conveyed to the dirt tank by the following grinding sludge. Flow rates for this type of magnetic separator depend on the type of inlet and its arrangement.

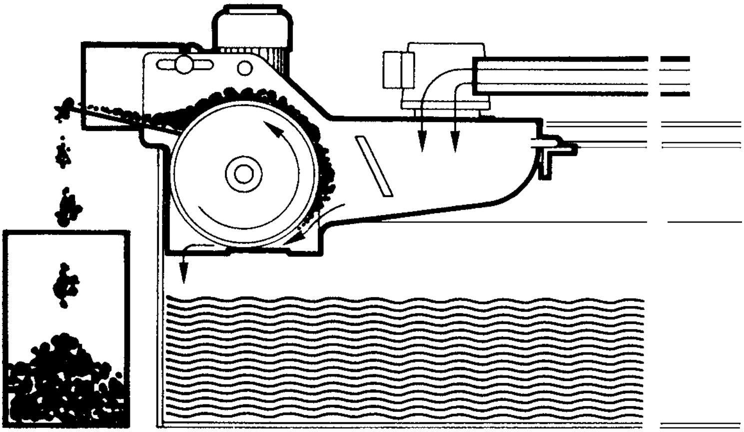


Figure 3.85 Magnetic separator schematic

High gradient magnetic separation

The attractive force exerted by a magnet on other magnetic materials in its vicinity is at any point proportional to the magnetic field and the magnetic field gradient at that point. A simple way of introducing large field gradients is to use a magnet in a highly sub-divided form, such as an assembly of fine wires or balls of a few mm in diameter. Large field gradients are then set up at the surface of the balls or wires.

The most efficient form of magnetic filter is one in which a large magnetic field is produced in a region occupied by a magnetic matrix in sub-divided form.

This arrangement is used in high gradient magnetic separation (HGMS) systems, as indicated in Figure 3.86.

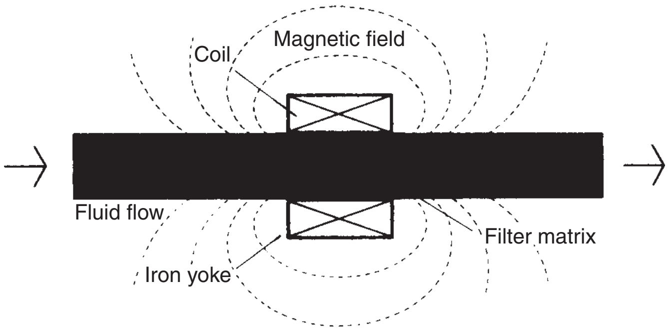


Figure 3.86 Principle of high gradient magnetic separation

Within this general arrangement there is considerable scope for design variations to meet the requirements of particular applications. For example, the magnetic field may be produced with zero power consumption, using a magnetized iron yoke. However, for ease of cleaning the filter, and also for reasons of economy of space, it is generally preferable to use a small yoke in association with electromagnetic coils. The shape of the yoke can be varied in a number of ways to obtain results compatible with the customer's requirements. Different filter matrices, such as expanded metal and ball bearings, are used depending on the application.

3U. ELECTRICALLY AIDED FILTERS

Electrostatic effects are the cause of two important but opposite phenomena in filtration, especially of gases. In the filtration of dusts from gases, it is possible for electrostatic charges to build up on the filter media. Should these reach a high enough level then a spark discharge could occur, and, if the dust mixture is explosive, a consequent explosion could result in serious damage to the filtration system. This risk can be minimized by making the filter medium conductive and then ensuring that its mounting connects it safely to earth. A conductive medium will have carbon fibres or metallic filaments embedded in it.

The opposite phenomenon makes effective use of the charges that almost all dust particles carry (and which can transfer to the filter medium to be the source of the charges described as hazardous in the previous paragraph). If the filter medium can be given the opposite charge to that carried by the dust particles, then the attraction of the electrical forces will cause the dust to separate more efficiently onto the filter medium. One way of doing this is to use fibres that are electrets (made from dialectric materials that carry a quasi-permanent electric charge or have a dipole polarization), or filter media carrying an excess charge (created, for example, by a corona discharge). Polypropylene or fluropolymers are suitable materials for this purpose. Electrically assisted filtration of this form is widely employed in air cleaning, especially for respiration.

3V. DEEP-BED FILTERS

The deep-bed filter (often called a sand filter, because that has for long been the filter medium used) is a clarification filter and has been the basic means of treating fresh water to render it safe to drink for over 100 years. The simple gravity sand filter is still its most common form, in terms of volumes of water treated.

The system involves operation of a filter with a deep bed of granular material as its filter medium, usually with the liquid flowing downwards under its own hydrostatic head. When full of dirt, the bed is normally cleaned by flow reversal, which expands the packed bed, releasing the trapped dirt particles and washing the dirt upwards and out of the vessel containing the bed.

Most commonly filled with sand, deep-bed filters may also use anthracite, coke, garnet and other inert solids as their filter media.

The gravity filter exists in two main types:

1. slow, characterized by a low water flow rate and a finer grade of sand, and
2. rapid, with water flow rates 5–7 times higher, and using a coarser sand.

The main difference between the two types is, however, in their mode of operation. The slow sand filter works by a straining action, exercised by a shallow layer of material on the top of the bed, which contains biological matter. This 'schmutzdecke' has both a filtering and biological destruction part to play in the water cleaning process. By contrast, the rapid sand filter aims for a truly deep-bed action, with contaminant solids adsorbed onto the bed material for most of its depth. Both are capable of giving treated water that is free of solid particles above 0.5 μm, from raw water as high as 50 mg/l in solids concentration (or even 500 mg/l).

The slow version runs with water rates of about 0.1–0.2 m/h, downwards through a bed of sand in the particle size range of 0.35–0.5 mm (uniformity coefficient up to 1.75). It sits, as a layer about 0.6–1.0 m deep, at the bottom of a concrete tank full of the raw water. For a new bed, time must be allowed for the schmutzdecke to form, which can mean running for a while at about one third of full capacity, and then slowly bringing the rate up to its full value. Once established, however, the slow sand bed can operate satisfactorily for considerable periods of time (weeks or even months) before the flow rate drops too far. Then the top layer must be scraped off the bed, and removed to another container for cleaning.

The rapid filter is around 0.75 m deep and formed of sand in the size range 0.5–0.6 mm (uniformity coefficient up to 1.7). It accepts a downwards water flow in the region of 5–15 m/h. It must be cleaned much more frequently than the slow filter, perhaps as often as daily. It is cleaned by reversing the water flow (using clean filtrate), at a much faster rate than the processing flow, so as to expand and fluidize the bed completely. The higher water flow rate and the fluidizing action together dislodge trapped solids into the wash water, which is removed to another separator for further treatment (usually a gravity settler, after flocculation). The backwashing flow is in the region of 30–35 m/h, and is usually augmented with air scouring at the base of the bed, or hydraulic jets on the surface. Backwash lasts only a few minutes and uses 1–5% of the throughput (and so has about 50 times the solid concentration of the raw water).

Whilst the backwash flow is a very effective means of cleaning the bed, it has also the feature that when the backflow is stopped, the fully expanded bed sinks back to its compact form, with all its constituent particles settling at velocities dictated by their size and density. The result is a stratified bed, with the coarsest and heaviest particles at the bottom, and the finest at the top.

Unfortunately this is exactly the opposite of what is needed for a downflow depth filter, which should have the raw water meeting the coarsest particles first and the finest last. Nevertheless, the rapid sand filter was used in this manner for many years, because to have an upflow filter risked the expansion of the bed in the direction of the flow, and the consequent release of trapped solids into the filtrate. It was not until the development of the Immedium filter in the 1940s that upflow became possible, by virtue of an open grid of parallel bars just below the surface of the bed.

The upflow filter was one of the major changes in the rapid sand filter in the second half of the twentieth century. Another was to operate it under pressure, which is done by building a cylindrical steel pressure vessel to contain the bed. Pressurized operation enables the filter to reach head loss figures 2 or 3 times those of the gravity filters. Pressurized filters offer the chance to operate at increasing pressures to counter the increase in head loss as the medium blocks up with trapped solids; however, declining rate operation is generally preferred, with the filter being backwashed when the flow falls below some predetermined value.

Another major development was the multimedia deep-bed filter, which uses the stratification action of the return from the fluidized state to create the better size gradations – by using two or three different materials of markedly different density as well as different sizes. Materials such as anthracite, sand and garnet are graded such that the lightest (anthracite) has the coarsest grains and the densest (garnet) the finest. Then in the resettling, the density factor is greater than the size factor, and the finer particles sink to the bottom. A downwards flow of raw water then reaches the coarsest layer first, as it should.

Continuous deep-bed filters

All of the types of sand filter so far discussed are discontinuous in their operation, even if the cycle is quite long in the case of the slow gravity filter. The most recent development of the rapid sand filter has been to make it continuously operating, by having the bed of sand or other materials move downwards through the filter (as in the DynaSand filter). The dirty solids normally fall into a conical hopper at the base of the filter, whence they are carried by a jet of air to a wash zone above the filter (as seen in Figure 3.87). Here they are washed clean of trapped solids and then returned to the top of the bed in the filter. There can now be no stratification of the solids by size or density, but the flow of water, counter-current to the movement of the solids, ensures good solids removal.

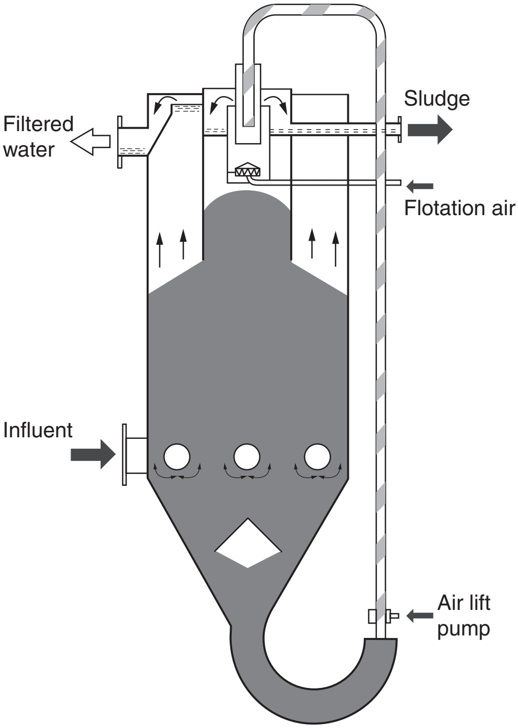


Figure 3.87 Continuous deep-bed filter

The same principle of the bed of solids moving continuously between filtration and cleaning zones has also been applied to the removal of dust from hot exhaust gas streams, the nature of the sand bed material being such as easily to resist the high gas temperatures.

4

LIQUID FILTRATION

SECTION CONTENTS

4A. INTRODUCTION

After a detailed look at the range of filtration equipment, the Handbook now turns to the major applications for the equipment, concentrating on the service or utility applications, but including water filtration, which overlaps the boundary between utility and process uses. This and the following section together examine the main liquid filtration applications, with engine fluids and hydraulic systems covered in Section 5, and all other liquid clarification processes covered in this section.

Water treatment, in one form or another, takes up the first four parts of this section, dealing with it as a liquid for drinking, washing and other related uses, as a process input (in food and beverage production or pharmaceutical processes, for example), as a utility (largely in the form of steam), and as a waste product from domestic and industrial activities, needing purification before it can be returned to the water resources whence it came.

The applications described here range enormously in size, from the very large purification processes used to turn raw surface or groundwater into drinking water, to the small membrane processes used to produce high purity water specific for pharmaceutical inputs. They also vary widely in technology, from the simple settling tank used as a preliminary clarifier, to the complex train of processes used to produce water for the washing of semi-conductor materials.

4B. BULK WATER FILTERS

The main water cycle starts, of course, with rain falling on the earth, most of it making its way to the sea by means of rivers, although the journey may be delayed by lakes. Water derived from the river/lake system is called surface water. The balance of the rain soaks into the ground and becomes held in underground aquifers (porous rock strata), from which it may eventually emerge as springs, if it has not been abstracted as ground water. From a purification point of view, the two types of water have very different needs. Ground water is essentially clean of suspended material, by virtue of its prolonged filtration by porous rock, but it is heavily loaded with dissolved matter (hard water) of many different kinds, and has the mineral taste accepted by many as the taste of pure water. Surface water, by contrast, has very little in the way of dissolved salts (soft water), but is frequently loaded with fine suspended solids and colloidal matter, with a lot of dissolved organic material, which gives the water a marked brown colour and an unpleasant taste.

Water abstracted for domestic or industrial purposes will come from whichever source is the most convenient, which usually means the nearest, so the raw water quality will be decided by the geology at the point of abstraction (for example, mainly soft from the impervious rocks of northern and western Great Britain, and mainly hard from the limestone hills of south-eastern Great Britain). The treatment processes required to convert raw water to fresh are thus largely dictated by the nature of the source of the raw water.

These treatment processes involve the purification of the raw water to a state fit to drink, which state is also good enough for many other domestic, commercial and industrial uses. Some end uses require a higher degree of purity, but the final result of the use of standard or high purity water is the same, namely the production of a large quantity of contaminated wastewater, sometimes highly contaminated. This then leads to the second major part of the water cycle, the need to treat the wastewaters adequately to permit them to be returned to the earth, in river, lake or sea.

That describes the main water cycle, relying on ‘fresh’ water sources, but the great majority of the earth’s water is that in the sea, which is far too salty for human or animal use, or for irrigation, and so must be desalted before it can be used for drinking or irrigation. The desalination of salty waters is a well established technique, but is an expensive one and very energy intensive. It is thus employed either where energy is cheap or there are no other sources of water. The cost of production from salt water is so much greater than that from fresh water that the incentive for water conservation is correspondingly greater, and the waste treatment component of the water cycle is of lesser importance in the total expenditure.

The global water situation is steadily worsening because of polluted groundwater, rivers and lakes, over-enriched and dirty seas, and water shortages within the growing populations of the less developed world. Water is, of course, essential if humans and animals and plants are to survive, and a major problem is that most people in the developed world take both hot and cold water for granted, and often squander it without reflection.

There is hardly any raw water treatment in the less developed world, and the standard of treatment is low in many other areas. Suitable technology does exist to achieve a satisfactory standard of water production, and, with the advent of greater political awareness of the problems and stricter environmental legislation, there are many opportunities to improve the world's water supply.

Raw water treatment

The conventional, and still the principal, type of filter used for cleaning bulk water is the sand bed, with backwashing carried out by a backflow of water, or preferably water backwash combined with an air scour. The latter results in better fluidization of the bed and more effective cleansing. Normally, such sand filters are downflow, gravity types, but upflow filters are also used where higher flow rates are required, or where high turbidities make conventional downflow sand filters impractical.

Metals and their compounds persist in the environment and can be a serious problem in raw water treatment, especially from ground water sources or surface water with a high proportion of agricultural run-off content. They may accumulate in organisms, particularly those near the top of the food chain, and cause a range of toxic effects. Metallic ions present in raw water arise from the leaching of minerals in the ground, from industrial effluents and chemical processes, and from leachates from land fill sites and contaminated land.

Bulk water treatment

Conventional downflow sand filters are effective for liquid-solid separation at flow rates up to about 15 $m^3/h.m^2$ of filter area, although higher rate downflow filters are available. With proper selection of filter media, gelatinous as well as granular suspended matter can be filtered out, without a rapid differential pressure build-up.

The bed is cleaned by a reverse, upward flow of filtrate water, sufficient to expand and fluidize the granules of the bed. When sufficient backwash liquid has passed through the bed, the bed particles settle back into place under the influence of gravity. If the particles are all of the same material, then the largest ones will settle at the bottom of the bed and the smallest ones at the top, which is the wrong way round as far as filtration is concerned, which is best achieved under downflow conditions by having the largest pores (created by the largest particles) at the top of the bed, first meeting the incoming raw water.

Typical filter media for the downflow filter consist of selected silica sands, and coal or anthracite, which are tough inert solids, available in a range of particle sizes. One solution to the problem of matching the pore sizes in the bed is to use layers of different solids, with different densities. If the denser material also has the smallest particle size, then the layers will resettle after backwashing with the finest at the bottom and the coarsest on top. The effect in a two-layer bed is shown in Figure 4.1, where the trapped solid concentrations are plotted for a conventional bed as well.

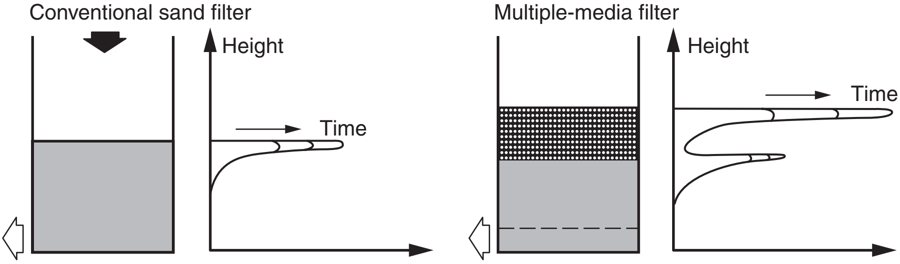


Figure 4.1 Downflow deep-bed filters

Materials for use in multi-layer downflow beds include anthracite, with a specific gravity of 1.4, flint sand (2.65) and garnet (3.83). Magnetite (4.9) can be used for a fourth layer if necessary.

A two-stage multi-media filtering system, shown in Figure 4.2 has been developed to treat turbid surface waters coming from rivers, lakes, reservoirs or the sea, but which are low in colour, iron and manganese. Whilst operational, oxidizing and coagulant solutions are injected into the primary (upper) vessel, and a further coagulant is also injected prior to the second (lower) vessel. The primary filter

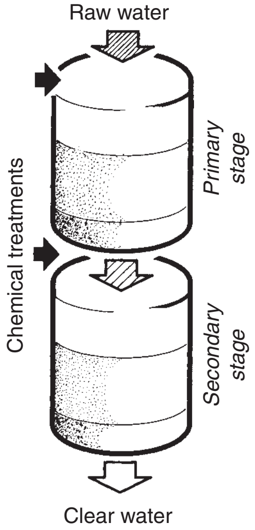


Figure 4.2 Two-stage multi-media filter

medium comprises anthracite, supported by a layer of silica sand. The secondary filter medium comprises a medium-sized layer of silica sand, supported by the final polishing layer of garnet or barium sulphate. The system has four programmable self-cleaning steps, using the normal backwash principle.

Upflow filters

The alternative approach to match flow direction with pore size is to undertake the filtration in upwards flow. With an upflow sand filter, flow is from the bottom through to the top of the bed. The result is that the entire bed depth is utilized to trap solids, with the fine top layer acting as the final cleanup zone. This gives a suspended solids capacity of 29 to 48 kg/m^2, depending on the density of the suspended matter, a greater capacity per unit of surface area than in a conventional downflow filter. A bed stabilizer is necessary at the top of the bed, to keep it in place during the high on-stream flow rates, in order to take full advantage of the bed's capacity to retain trapped solids. The bed is cleaned by upwards flow of backwash liquid, but the bed is expanded by air agitation prior to washing, in order to achieve maximum cleaning efficiency. This mode of operation allows the upflow filter to handle turbid waters at high flow rates with longer cycle lengths, while ensuring good cleaning cycles.

The bulk filtration units so far described operate under gravity, because they involve very large quantities of raw water and, in consequence, are very large units in order to cope with the flow (Figure 4.3). A possible alternative approach is to pressurize the containing vessel, and pump the raw water into the filter, so increasing the pressure differential across it and thereby increase the flow rate. This is a much more expensive process, and tends to be used for small demand/high quality treatments, which may involve chemical processes as much as filtration.

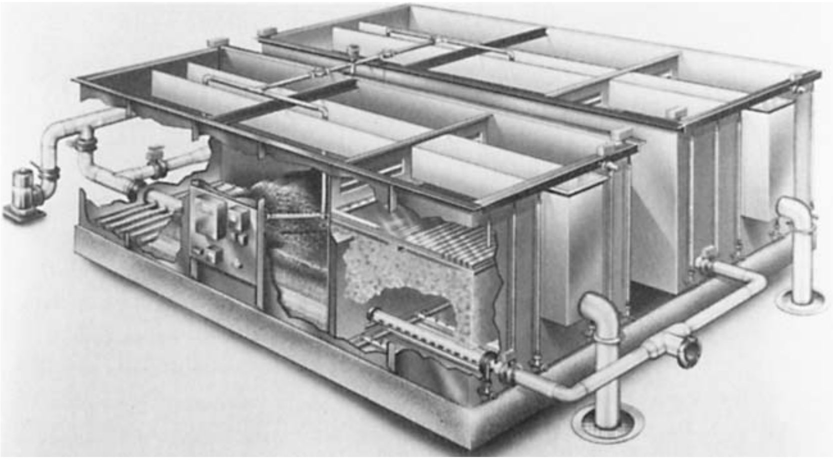


Figure 4.3 Bulk water treatment plant

Thus, Figure 4.4 shows a pressure vessel filter, operating in upflow mode, and developed for the removal of dissolved iron from water supplies. The filter medium takes the form of a bed of catalysed manganese dioxide in granular form, approximately 1 m deep. This medium has the ability to cause dissolved iron to react with the oxygen present in the water to form insoluble iron oxides, which will precipitate and be retained by the bed. Cleaning is then undertaken by a high velocity backwash process which fluidizes the bed medium and removes the precipitated iron.

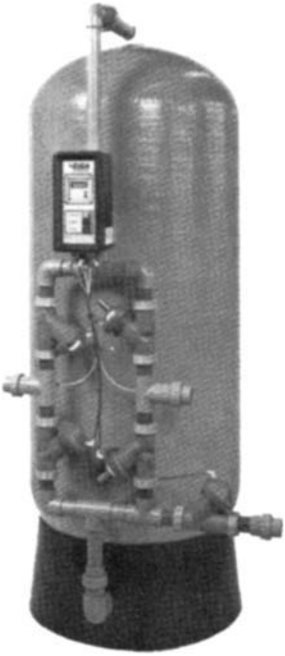


Figure 4.4 Pressure filter for dissolved iron removal

Moving bed filter

The major development of the deep-bed filter has been to allow the bed material to move continuously down through the filter vessel, and then to be carried back up to the top of the bed, through a cleansing zone. Manufacturers have concentrated on the development of the moving bed filter, which provides better cleansing of the bed, and which does not have to be shut down for back washing. It is thus a truly continuously operating filter. Figure 4.5 shows an example of a typical continuous self-cleaning sand filter. It has no mechanical moving parts yet it is possible to obtain feed flow rates of up to 25 m^3/h per square metre of filtering area.

The main structure of the filter is a cylindrical tank with a conical bottom. In operation, the raw water is fed in (1) where an inlet system, and (2) evenly distributes the flow into the filter bed. This bed is made up of sand of a predetermined

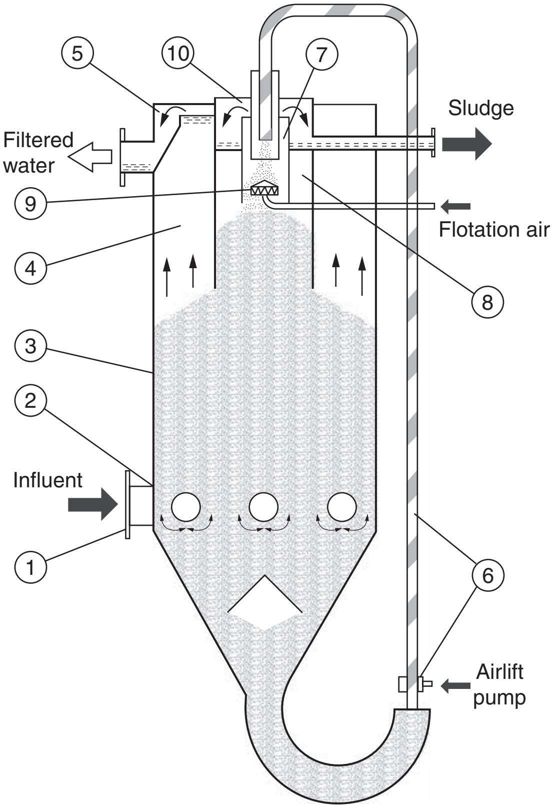


Figure 4.5 Moving bed sand filter

grain size, selected according to the nature and quantity of suspended solids in the raw water. The water flows through the sand bed and leaves the filter at the overflow weir (5). The sand bed moves continuously downwards, being sucked from the bottom by an airlift pump (6), which carries the dirty sand upward to the top of the filter into the sand washer (7).

The washed sand falls back into the filter through the chamber (8). The pressure drop across the filter remains at a constant low value by virtue of the continuous washing process that keeps the filter bed clean. The heart of the system is the sand washer, which, via the airlift, receives a concentrated mixture of sand, water and dirt particles; the dirt is separated from the sand by flotation due to the action of micro air bubbles generated at the air diffuser (9). The sand washer is designed to clean each grain of sand by scouring. The dirt particles are floated upward by the air bubble action and leave the filter over the sludge weir (10), and are carried away by some of the wash water. This reject water is a small fraction of the total water fed to the filter, and is returned to the filter inlet after the sludge is dewatered.

It is recommended that a filter screen be used ahead of and in conjunction with filters of this type. Continuous self-cleaning filters of this kind are considered to be one of the most reliable types of bulk water filter available, with low plant costs and high clarification efficiencies. A full scale array of moving bed filters is shown in Figure 4.6.

Figure 4.6 An array of moving bed filters

Rain water recycle

Much thought is currently being given to the immediate collection of rainwater and its use for low grade fresh water applications, such as toilet flushing, garden irrigation and so on. An automatic system that collects rain and wastewater from roofs and pavements in and around a building, stores it in a tank and then filters it to produce a pure supply is shown in Figure 4.7. The system can remove all organic compounds including oil, grease and detergents.

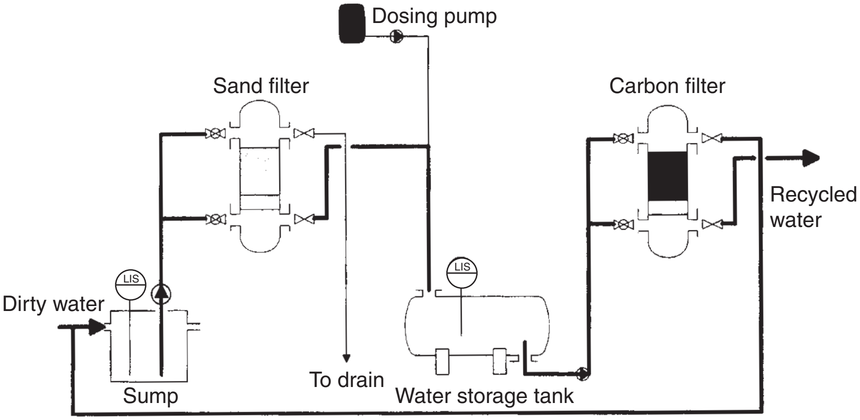


Figure 4.7 Rainwater recycling plant

A similar approach is now being adopted to the recycling of so-called ‘grey water’, which is all of the water going to the domestic drain except that from toilet flushing. This includes bath and shower water, and laundry waste. It might also include kitchen sink drainage, provided that this has no toxic content.

The main problems with rain and grey water recycle are public acceptance, and the cost of very different plumbing circuits, to take two grades of water around the house or apartment building.

Cooling water systems

The ubiquitous hyberbolic cooling tower is one of the most evocative sights when the theme of ‘industry’ is discussed. Its plume of steam – assumed to be a more toxic effluent – is a symbol to many of the environmental impact feared from industrial activity. The plume is, of course, a sign of heat going to waste, so it should be a slowly diminishing sight.

Cooling systems for large plants (factories, power stations, etc.) are of two types: once-through and recirculating. The once-through systems are typified by the large power stations situated by the sea or on large rivers, which take in their cooling water, treat it as necessary, use it and discharge it back whence it came. The circulating systems have a stock of water which is used for cooling, then is itself cooled to dispose of the remaining heat (in, for example, the above-mentioned cooling towers), and is then returned to stock.

As far as the filtration business is concerned, the cooling water must pass through heat exchangers of some kind, whose basic performance is dictated by clean heat transfer coefficients, but whose actual performance is reduced as deposits of one kind or another form on the heat exchange surfaces (some of which are in the form of narrow channels, or are otherwise inaccessible). It is the job of the filter system, which must be installed ahead of the heat exchangers, to remove the suspended material – animal, vegetable or mineral – from the cool water.

Clarification of cooling water is necessary whichever of the two main types of system is in use. Once-through cooling has to deal with whatever quality its source has at the time of abstraction, so has a rather more expansive treatment process, certainly as far as the intake end is concerned. Recirculating systems on the other hand should have only a small proportion of make-up water to deal with (to make up for the water lost by evaporation), but also have to remove suspended solids picked up from the cooling flows themselves.

The degree of filtration required will depend upon the quantity of water to be treated, and the quality of treated water necessary to maintain the heat transfer surfaces as clean as possible. A strainer of some kind will be needed as the intake filter, ahead of a finer filter such as a deep bed system or a multi-bag filter. It may even be necessary to include ultrafiltration as the final step if there is much organic or colloidal matter in the intake water.

The warm water in the cooling tower pond and the accumulated organic material provide perfect growing conditions for bacteria. Outbreaks of Legionnaire’s disease associated with cooling water systems are a cause for serious concern. The conditions under which the bacillus *Legionella pneumophila* can develop in water systems and be transmitted into the environment are varied and complex. A cooling tower of average size can collect between 2 and 3 kg of solid matter every day, including dust, engine exhaust, pollen and insects. Together, these create a biofilm within the system, particularly in the low flow zones of the cooling tower pond, which can act as a food source for bacteria. It is estimated that the cost to UK industry and commerce of this water fouling is in the region of US$1.5 billions per year.

Much work is being undertaken in evaluating the alternatives to the commonly used biocides for the control of biofouling in cooling systems. Alternatives such as bromination, ozonation, ultraviolet treatment and pasteurization are all being tested. Biocidal efficiency depends, of course, on the quality of the circulating water. Build-up of inorganic and organic debris within the circulating water interferes with biocidal activity and filtration has long been recognized as a way of maintaining biocidal efficiency. Modern filter media and membrane systems permit the removal of bacteria, and so these are becoming an important component of the purification process.

Not all cooling systems are huge, and some are well catered for by use of self-cleaning units such as that shown in Figure 4.8. This is a typical example of an effective automatic filter, which shows three filter elements (here called pods) in use

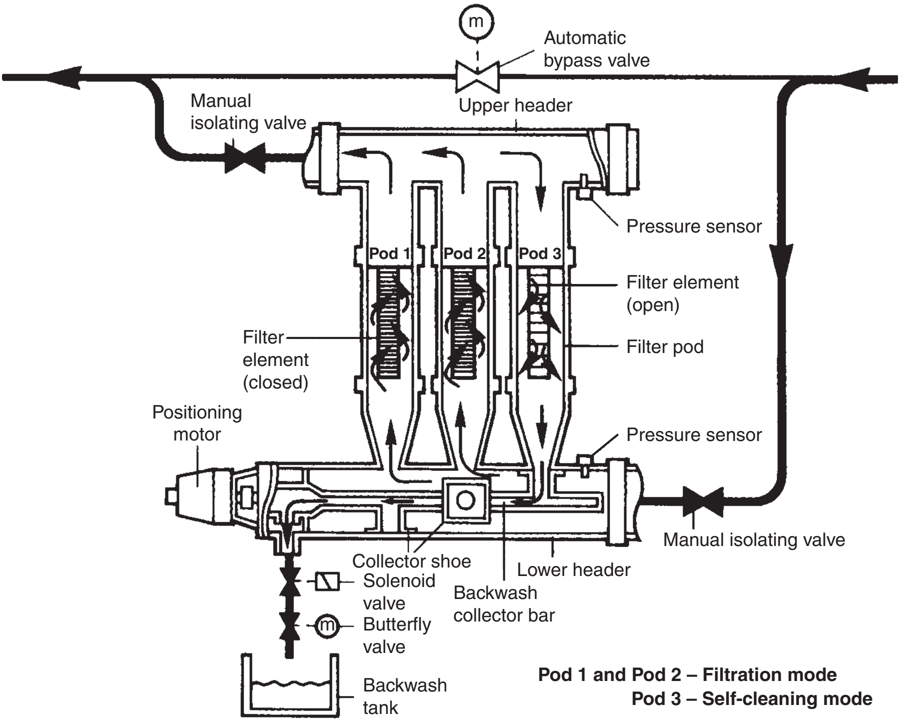


Figure 4.8 Automatic self-cleaning filter system for cooling tower circuits

in parallel. Under normal filtering operation, all filter pods are in use, and the control system monitors the pressure drop between the upper and lower headers. When the pressure drop reaches a preset level, the collector bar is rotated by the positioning motor until a shoe is aligned over the first pod. While the remaining pods continue the filtering operation, the backwash valves are opened to allow a portion of the filtered water to backflush the first pod. In this way, the filter elements are opened and the contaminants are flushed away to waste, usually a backwash collection tank. Each pod is cleaned in this way in turn, and finally the backwash valves are closed and the filter reverts to full filtering mode.

The elements using this type of filtration system are formed from a continuous high grade stainless steel wedge-wire spiral coil. Raised ridges on the upper surface of the coil ensure a precise filtration gap to the required separation rating. Standard ratings are usually 12, 25 and 120 µm. During self-cleaning, liquid flow is reversed and the compression of the spring is relaxed a trifle. The gap between the turns of the coil thus increases, allowing the contaminants that become compacted into the wedge-wire structure to be removed during backwash. An automatic bypass valve is normally installed around the filter. This valve is linked to the control system and opens automatically should the filter become blocked by objects that cannot be backwashed out.

Based on the same wedge-wire screen element, the in-line filter shown in Figure 4.9 is self-cleaning and suitable for filtering industrial water as well as small cooling water

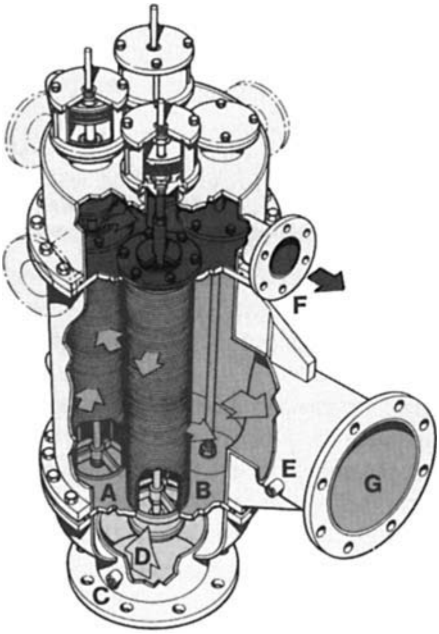


Figure 4.9 In-line filter for industrial water. A, Element backwashing; B, element filtering; C, high pressure connection; D, inlet; E, low pressure connection; F, backwash discharge; G, outlet

installations. Separation to the required level occurs as the water passes through to the interior of a stainless steel wedge-wire screen. As a build-up of contaminant occurs on the screen a pressure difference is registered and increases to a preset limit, and then initiates the backwashing of one screen, whilst the remainder of the elements continue to clean online. The screens are cleaned individually and in sequence.

Desalination

Various methods from evaporation to distillation and chemical treatment may be employed for producing fresh water from sea water and other salty water sources. The different types of technology employed include multi-stage flash distillation, thermo-compression distillation, reverse osmosis and reverse electrodialysis.

A multi-stage flash distillation plant typically consists of a series of twenty or more chambers, each operating at a lower pressure from the last. As heated brine flows from one chamber to the next, some of it flashes off into water vapour. This passes through moisture separators that remove any entrained droplets of brine. The vapour condenses on colder condensation tubes, and drips as distillate into trays from which it is led away to storage.

A thermo-compression distillation plant usually has two to six evaporator stages and uses a multistage thermo-compression process operating at quite low temperatures and sub-atmospheric pressures. In a typical four-stage unit, source vapour introduced at, say 62°C and 0.22 bar, into the condenser tubes of the first stage is condensed by externally sprayed raw water and the condensate is drawn off as product. In cooling the condenser tubes, the raw water in stage one is heated and part of it vaporizes at a lower temperature and pressure, say 58°C and 0.19 bar. This vapour enters the tubes of the second stage, is condensed by raw water as in stage one and is also drawn off as product. Part of the raw water in the second stage is vaporized at still lower conditions, say 54°C and 0.15 bar, and enters the tubes of the third stage. The process is repeated, and again in stage four.

Part of the vapour produced in the fourth stage is drawn up at 46°C and 0.10 bar by the thermo-compressor, which compresses it with high pressure steam at 0.22 bar to feed the first stage. The condensed vapour from each evaporator stage and from the condenser stage is extracted by a pump to form the product water. Thermo-compression distillation plants can produce very pure water from any sea water or brackish source without a complex pretreatment or filtration.

For many years salt water was purified by distillation processes, in relatively small quantities (such as on board a passenger ship, or in a desert town) because of its energy intensity. The development in the early 1960s of desalination by reverse osmosis, using a membrane as the separating medium, completely changed the desalination picture, making it much more accessible, even if still not as cheap as deep-bed filtration.

Reverse osmosis

If a tank is set up divided into two compartments by a vertical barrier that is permeable to water only, and one compartment is partly filled with pure water and the other is filled to the same level with a salt solution, then the chemistry of the system is such that water will flow through the barrier, from the pure water side into the solution, in an attempt to make the salt concentrations the same on both sides of the barrier (which it obviously cannot do, as that would require an infinitely great amount of water).

This flow of diluting water is termed osmosis. As osmosis continues, the amount of water on the pure water side decreases, and the volume of the solution increases by the same amount, the result being a steady increase in the separation of the liquid levels on the two sides of the barrier. The increasing level of the solution over the pure water level creates a hydrostatic pressure difference across the barrier, which slows down the rate at which the water moves through to the solution side. Eventually a physical equilibrium is reached, in which the hydrostatic head equals the force exerted by osmosis, and water flow ceases. The head at which this occurs is called the osmotic pressure of the solution, and this varies with the concentration of salt in the solution: the higher the concentration, the greater the osmotic pressure, and also with the solution temperature.

If the solution side of the tank is now enclosed and pressurized, water is forced back through the barrier and out of solution, with the speed of reverse flow increasing as the applied pressure rises. This situation is called reverse osmosis, and is the basis for the desalination of water – by the application of pressures in excess of the osmotic pressure to a solution restrained by a semi-permeable membrane.

It is, of course, true that no membrane can be 100% in rejecting the passage of salt through it, and therefore that the permeate from a reverse osmosis process will always have a slight salt content. The exact purity of this permeate depends on the concentration of the brine and on the salt permeation constant of the membrane.

This is a high pressure process. Sea water osmotic pressures can be in the region of 34 to 42 bar, and the net operating pressure for a reverse osmosis system, which is that required to provide an economic product water flow rate, ranges typically from 17 to 28 bar. As a result, the actual applied operating pressures are in the range of 50 to 70 bar. The applied pressures for brackish waters range from 14 to 48 bar, depending on the feed water salinity levels.

The rate of permeation of pure water through the membrane is proportional to the difference between the applied and the osmotic pressures, i.e. to the net driving force. As this is increased, the water flow rate increases while the salt flow remains constant, so that increasing the pressure, and therefore the flow rate, gives decreasing salt concentration in the permeate or product water.

Reverse osmosis membranes

The key to the desalination of water by reverse osmosis lies in the proper selection of the membrane through which the separation of salt and water occurs. The original RO membranes were made from cellulose derivatives, but are now much more likely to be made from synthetic polymers.

Two membrane formats are most commonly used for reverse osmosis, the spiral-wound type and hollow fibres. A hollow fibre module is made from a bundle of hollow fibres, each of which has the salt rejecting layer on the outside surface, and an outside diameter of 90 to 100 μm, with an inside diameter of about 45 μm. The ends of the fibres are embedded into an epoxy sheet, which is then sealed into a cylindrical glass fibre pressure vessel. The fibres can extend the full length of the containing cylinder, but it is more usual for the bundle to be bent in the middle into a U-shape, with the two ends adjacent in the housing.

The raw water is fed into the housing and part of it permeates through the walls of the fibres to discharge from the open ends of the fibres into the end-cap of the housing. The rejected brine is discharged from the other side or end of the housing cylinder. Hollow fibre modules provide compact systems, and the large membrane surface area resulting from the high density packing of the fibres compensates for the relatively lower water permeability of this configuration.

The spiral-wound element typically embodies a flat sheet membrane, cast on to a porous polyester support sheet. Several membrane/support sheet combinations, together with intermediary spacer sheets (for liquid flow) are then wound round a central core (Figure 4.10). The membrane can be made from a cellulosic polymer or it may be of the thin film composite type, where the polyamide salt-rejecting layer is applied to a microporous polymer film, which in turn is bonded to the support sheet. The central product water tube, around which the membrane and its supporting layers are wound, collects the fluid that permeates through the membrane. The spiral element operates as a cross-flow membrane filter. Only a proportion of the brine permeates the membrane to become product water, while the residual brine maintains enough turbulence to minimize the build-up of rejected salts ions that might otherwise clog the membrane surface.

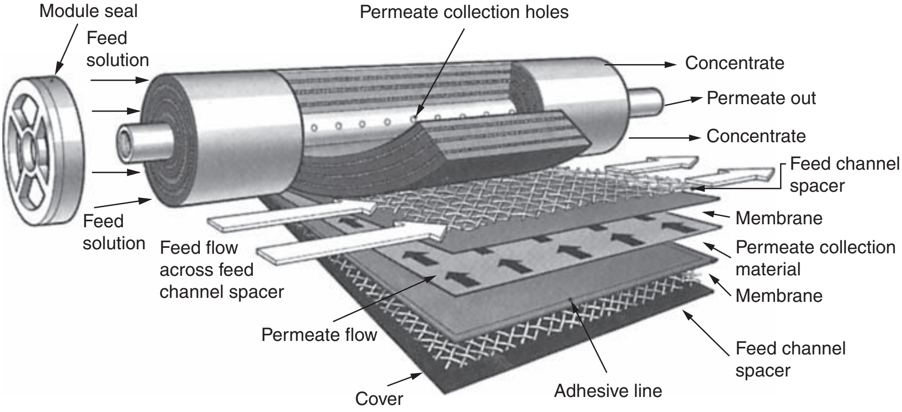


Figure 4.10 Spiral-wound membrane module

The narrow passageways in reverse osmosis modules allow ready blockage by even quite small rogue particles. It is thus necessary to provide reverse osmosis plants with prefilters that ensure freedom from such particles.

Reverse electrodialysis

Water desalination by the reverse electrodialysis process is less commonly employed than reverse osmosis. It typically uses two types of ion exchange membrane, one allowing only the passage of negatively charged ions (anions), and the other only allows the passage of positive ions (cations). Electrodialysis was (and is) a laboratory process, used to remove salts from certain colloidal solutions, but the development of membranes with selective permeability in relation to anions and cations has totally reactivated the process.

The ions, from the feed water to be desalted, migrate towards the membranes on the application of an electric field (Figure 4.11). Anions pass through the anion-exchange membranes and cations through the cation-exchange membranes, in opposite directions. Both ion flows are then stopped by the next membrane that they reach, because it is only permeable to ions of the opposite charge. The ions thus held in alternate compartments combine to form a concentrated solution of brine.

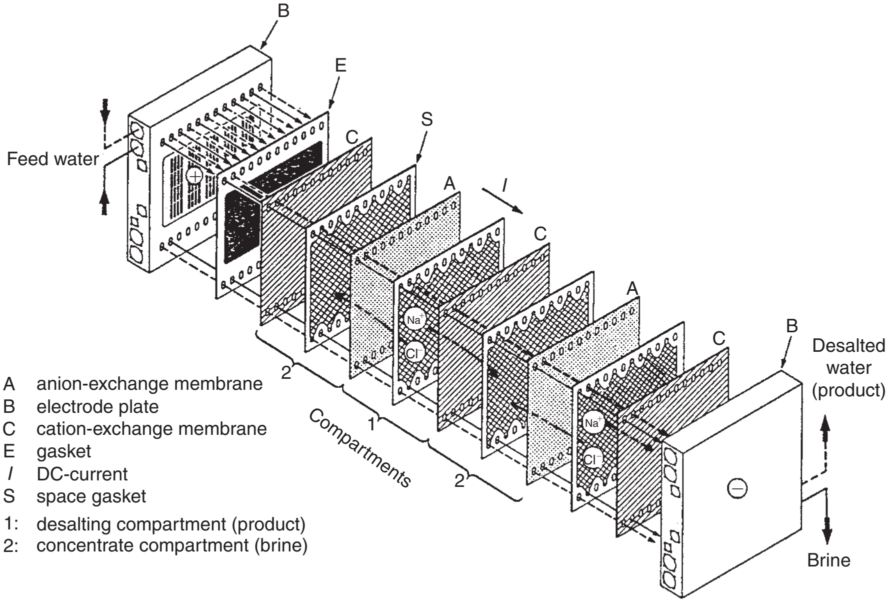


Figure 4.11 Reverse electrodialysis process

In practice an electrodialysis stack is typically composed of a large number of such compartments, separated alternately by anion- and cation-exchange membranes. The electrolyte solution in contact with the electrodes, where electrochemical reactions take place is circulated in a separate circuit. Periodically, the polarity of the electrodes is reversed, so that the ions migrate in the opposite direction, and the brine and product water compartments are interchanged. This procedure provides an automatic cleaning of the membranes, without any need for the use of cleaning chemicals.

Some idea of typical operation costs of desalination processes is given in Figure 4.12, plotted against the salt concentration of the water to be desalted. Although the cost data are by now a little old, the relative costs as between the various processes are still roughly right. It can be seen that, for all but the lowest concentrations, reverse osmosis is the least expensive option.

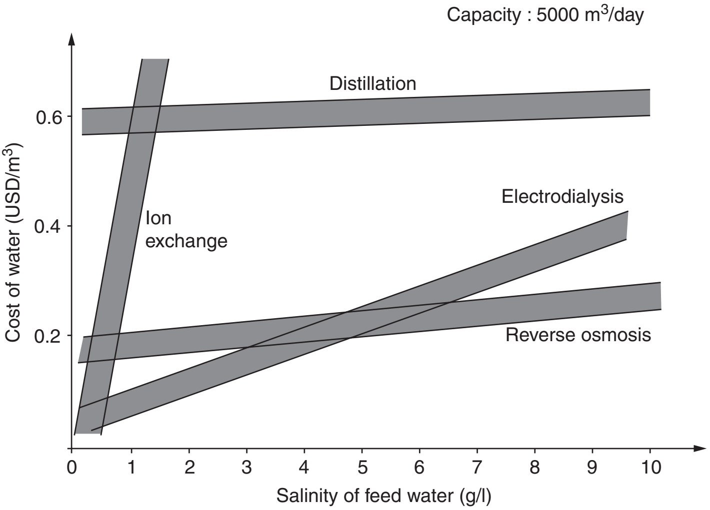


Figure 4.12 Desalination process operating costs

It can be seen that the membrane has a major role to play in the provision of pure water: the removal of dissolved salts (reverse osmosis, and, more recently, nanofiltration), high quality filtration, trihalomethane compound reduction, silica removal – all being possible with the appropriate membrane process.

4C. DRINKING WATER FILTERS

The bulk water treatment processes described in Section 4B produce water that is good enough to drink, and which is vastly better than that drunk by millions of people in the developing world. Nevertheless, it is not good enough for many people, and greater degrees of purification are accordingly necessary to satisfy these needs. This is true for drinking water, the subject of this part of Section 4, and for water to be used in industrial processing (covered in Section 4D).

The major concerns among consumers are colour, odour and taste, the presence of which in tap water has driven the market for bottled water to such high levels (coupled, of course, with its portability). A more important concern should be the presence of pathogenic micro-organisms, but this only hits the public consciousness when there is a disease outbreak.

Drinking water contaminants

The World Health Organization has identified 752 substances that can be present in tap water. Water authorities are obliged to monitor the levels of only 66 of them, and bottled water manufacturers only 28. Up until about 30 years ago, lead was thought to be the only dangerous pollutant in drinking water. Today, in addition to lead, pesticides, bacteria, viruses, coliphage, nitrates, chlorine, chloro-organics and aluminium must be added to a growing list of health hazards. Contaminants typically found in water are shown in Figure 4.13.

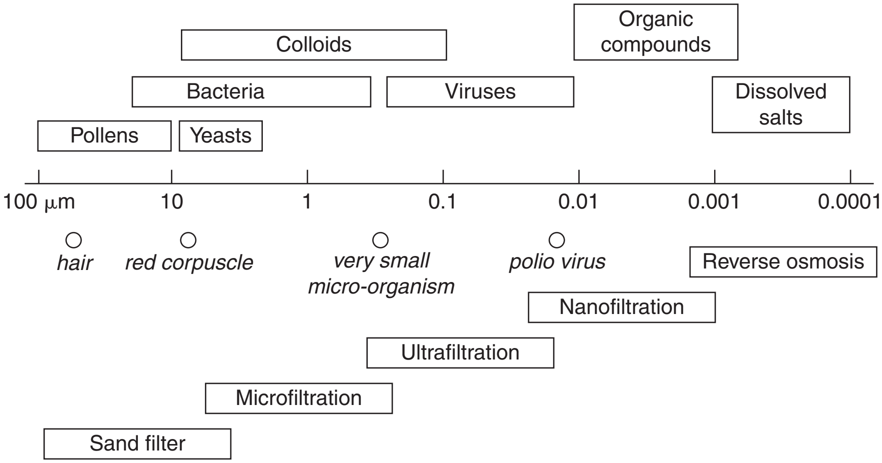


Figure 4.13 Contaminants found in drinking water

Chlorine has been widely used by water authorities as a sterilizing agent, and hence its appearance in a list of water contaminants. However, chlorination is no longer believed to be completely effective as a method of killing bacteria, because of the need to use excess chlorine to last from the works to the domestic tap, hence the imparting of an unpleasant taste and an odour to drinking water. Another side effect of chlorination is now giving rise to concern: chlorine reacts with small particles of organic compounds to create a group of compounds called trihalomethanes, which are under increasing suspicion from toxicologists.

Bacterial diseases, which are usually spread through water contamination, are a cause for major concern throughout the world. Cholera is very widespread, despite the fact that huge numbers (about one billion) of the cholera bacteria are needed to cause infection.

The parasitic protozoan *Cryptosporidium* is also widely distributed in nature, infecting a wide range of hosts including farm animals and pets. The protozoa get into the water supply from animal excrement. The problem is that they form a protective stage known as oocysts, which allow them to survive for long periods in water (up to perhaps eighteen months) whilst waiting to be consumed by a suitable host. Once infected, a host becomes a lifetime carrier, liable to relapses – and it only takes a single *Cryptosporidium* oocyst to cause infection. In normal patients, *Cryptosporidium* gives rise to self-limiting gastro-enteritis, which can last for up to two weeks. If the patient is immunosuppressed, infection is life threatening.

Cryptosporidium is widespread in drinking water resources. The cysts are only 4–7 μm across, and are very difficult to detect and remove from water by conventional water treatment (but are easily removable by micro or ultrafiltration). They also resist chlorine.

Giardia lamblia is another oocyst that causes disease, but, unlike *Cryptosporidium* it is treatable with antibiotics. Both *Giardia* and *Cryptosporidium* can be killed by boiling the water for twenty minutes, but, unfortunately, boiling concentrates metals such as lead and aluminium in the water.

Bacteria and viruses may be eliminated from water by ultrafiltration membrane separations, or just bacteria by using microfiltration. On the small, local scale membrane filter units are ideal for treating drinking water, especially if coupled with an activated carbon element to remove colour and unpleasant taste.

In the laboratory, filter life may be assessed in various ways, e.g. by chlorine break-through showing the end of life of an adsorbent element, the bacterial counts in the effluent, colour tests, and differential pressure (indicating clogging of the filter). Bacterial count tests are obviously of major significance.

Apart from chlorine and hydrogen sulphide, the origin of bad tastes and odours in raw waters are usually organic contaminants. Here, the ability of a filter to remove methylene blue from water is a standard and demanding test for organics removal capability. The longer a filter can continue to deliver clear filtrate when fed with methylene blue loaded liquid, the better its ability to cope with organics. This particular test is a simple one by which to compare the performance of different filters.

Groundwater sources

According to a US congressional study, groundwater contamination will become a principle environmental concern for the next decades. Once contaminated by toxic organic chemicals, groundwater can remain polluted for hundreds or thousands of years, if not for geological periods of time, because nature supplies few, if any, cleansing or diluting processes for groundwater.

The most common sources of this pollution are the thousands upon thousands of industrial waste sites, leaking underground storage tanks, improperly treated sewage and, probably the most common of all, agricultural chemicals trickling and seeping into underground water aquifers. Millions of private and municipal water wells and storage lakes are either contaminated now, or are in danger of becoming contaminated as chemicals creep through these aquifers. A recent example of underground tank leakage was the appearance of MTBE (a petrol performance improver) in groundwater, leaking from petrol station storage tanks – which has led to the phasing out of MTBE as an additive.

Domestic water treatment

Tests confirm the presence of these toxic substances in drinking water, but few mains cold water lines into residential properties incorporate an effective filtration system. Ideally, drinking water should be organoleptically neutral, clear and mineralized sufficiently to give it the 'fresh' taste. It should be free from any organic matter that reacts with chlorine, and very low in biodegradable compounds, so as to impart enhanced biological stability. It should also be devoid of other undesirable matter even in trace quantities.

These requirements can be achieved in a good mains-supply drinking water filter system, and Table 4.1 shows the contaminant removal of such a system, which would include a combination of mechanical filtrations of several types plus adsorptive contaminant removal.

Table 4.1 Contaminant reduction levels

Contaminant removal:		(> = more than)	
Bacteria:		**Metals:**	
E. coli	>99.9999%	Lead	>99.5%
Total coliforms	>99.9999%	Aluminium	>97.9%
Shigella	>99.9999%	Cadmium	>99.5%
Typhoid	>99.9999%	Chromium	>99.3%
Cholera	>99.9999%	Copper	>98.4%
Salmonella	>99.9999%	Mercury	>99.5%
Legionella	>99.9999%	Iron	>73.7%
Campylobacter	>99.9999%	Arsenic	>98.3%
Cryptosporidium	>99.9999%		
Giardia	>99.9999%		
Chlorine and THMs:		**Pesticides and herbicides:**	
Chlorine	100%	DDT	>99.99%
Chloroform	>99.99%	Simazine	>99.99%
Dichlorobromethane	>99.99%	Atrazine	>99.99%
Dibromochloromethane	>99.99%	Lindane	>99.99%
Dichlorodifluoromethane	>99.99%	Melathion	>99.99%
Dichlorodiphenyltrichloroethane	>99.99%	Dieldrin	>97.5%
Carbon tetrachloride	>99.99%		
Trichloroethylene	>99.99%	**Nitrates**	>99.99%
Tetrachloroethylene	>99.99%	**Nitrites**	>99.99%
PAHs	>99.99%	**Sediment and algae**	>99.99%

In the case of domestic premises, it is up to the householder (or the management of an apartment block, or hotel or hospital or other institution) to decide how much additional treatment to give to the mains water as received. If the water arrives turbid, then some kind of mechanical filtration would be advantageous, perhaps a sand bed or a replaceable element microfilter. If the water is coloured or possessed of an unpleasant taste and/or smell, than an activated carbon filter would be advisable. If there is concern over bacterial removal, then a membrane system would be needed, capable at least of microfiltration, and possibly ultrafiltration – but this is now starting to be expensive.

On the smallest scale, point-of-use treatment can provide considerable comfort. This may take the form of the kitchen counter top water jug containing a filter cartridge such as that supplied, very successfully, by Brita – which then treats only that water whose drinking and food washing characteristics are of concern. A permanent filter housing using a similar cartridge (turbidity, taste and colour removal plus bactericidal action) can be plumbed under the worktop to provide a similar level of protection.

For anything larger than the single tap, a packaged plant can be supplied, with filter and activated carbon cartridges, probably in duplex format, enabling easy removal for cleaning or replacement.

Other important features for the local filter are that the filter unit should be easily sealed, the media should be non migrating, and the whole should be heat resistant if it is to be used with hot water. It should also be easy to mount as an in-line fitting and easy to disassemble to change the filter cartridge. Disposable cartridge filters are preferable to cleanable filters, as it is not generally possible to remove all bacteria by cleaning; also filter media may be damaged and lose their efficiency by heavy cleaning. Accepting activated charcoal, usually combined with a silver sanitizing agent, as the main element, the additional elements used for ultra-fine mechanical filtering will finally govern the overall performance.

It is also desirable to obtain an optimum balance between what is removed and what is passed by the complete filter: some soluble mineral salt content in the final product may be desirable, rather than removing as much dissolved mineral matter as possible (which leaves a ‘flat’ taste).

Filter housings made from plastic should be protected against freezing. Failure to do so may result in cracking of the filter and water loss. The capacity of the filter has to be tailored to specific needs, generally rated in terms of the quantity of water that the filter can treat before the cartridge needs replacement. This can only be an approximate rating and is very much dependent on the condition of the water being treated, the water pressure (in a pressurized system), and any pressure cycling. If the input water being handled contains a relatively high proportion of suspended matter, the life of the clarifying filter cartridge can be considerably extended by the addition of a relatively coarse prefilter in the system, at a position where it is readily accessible for cleaning.

Temporary water supplies

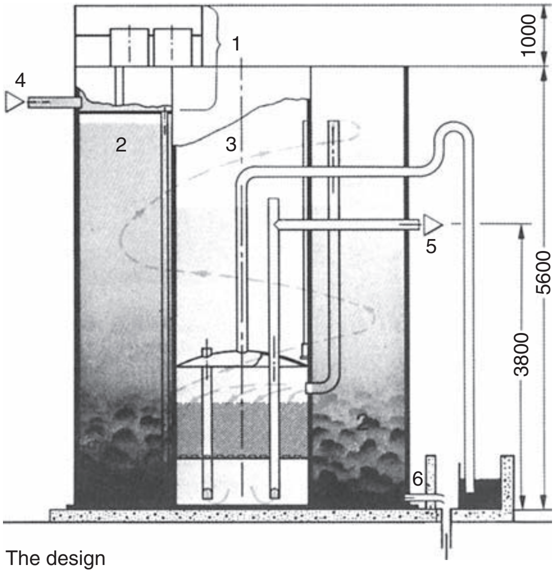
Hundreds of thousands of touring recreational vehicles, caravans and mobile homes, together with pleasure boats of all types and sizes, rely on onboard tanks for personal water supply. There is a correspondingly large number of temporary water users, such as construction sites, camps in remote areas, fishing boats, and so on, all needing a supply of water that is sanitary, and remains so for as long as needed.

Pleasure craft, for example, load a tankful of water from the mains supply at a marina – a source that may also be used for wash-down purposes. Even with the use of a hygienic connecting hose, there is a strong chance that the initial flow from the source will be contaminated. It is thus recommended that an in-line filter be used in the feed line from the mains to the tank.

Further contamination is then inevitable on standing. Tests conducted with a large plastic container filled with tap water showed an initial bacterial count of 18/ml, which, after only a week, had risen to 45,000/ml. Thus, the equipment commonly used to store and dispense fresh water in mobile environments leaves much to be desired, unless it is subject to additional treatment. This may range from the simple use of purifying chemicals added to the water, or filtration or a complete water treatment system. Of these, filtration is by far the most attractive of the low cost methods.

In large applications, automatic gravity filters are often used for the treatment of mains or groundwater, including aeration, removal of iron and manganese, and deacidification.

The unit shown in Figure 4.14 is designed to supply sufficient quantities of drinking water in accordance with WHO standards for camps in remote areas, temporary construction sites or hazard areas. The system combines flocculation, chemical feeding and filtration in one unit. Up to 35 m^3/h of raw water can be treated without the need for the use of pumps, agitators or mixers within the main treatment zone, as



The design
1 Chemical feeding and mixing system
2 Reaction tank for flocculation and sedimentation processes
3 Automatic gravity sand filter inside the reaction tank
4 Raw water
5 Clear water
6 Sludge outlet, ring conduit

Figure 4.14 Local drinking water filtration plant it simply uses the height of the water to provide the driving force. To obtain this hydrostatic head, raw water needs to flow into the reaction tank through a chemical mixing system at a height of 5.6m. The feeding tanks are located 6.6m above the ground.

The raw water, enriched with flocculant chemicals, flows into the bottom part of the reaction tank, causing an upward spiral current. The settled matter in the form of a sludge is periodically removed from the reaction tank by means of a ring conduit placed near the bottom of the settling tank. The pre-clarified water then flows down into the automatic gravity filter from the top of the water surface level of the reaction tank. By its own head the water moves down through the filter layer and out to service.

During emergencies the provision of clean portable water from a natural water source is paramount. This sort of plant can be packaged, perhaps into a container (Figure 4.15), and transported anywhere around the world by air, road or sea, and is used to remove contaminants from a natural water source. Such containerized plant can also be used in a number of applications from short-term emergencies at a water treatment works, to stand-by use when a permanent plant is temporarily shut down.

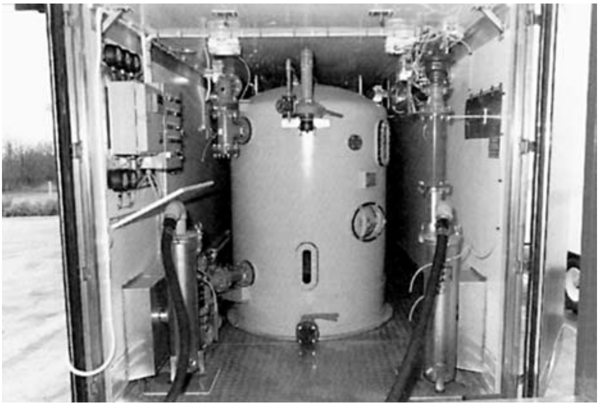


Figure 4.15 Packaged water treatment plant

Biological treatment

A packed bed of activated carbon, acting as an adsorbent, is a very good purification means for small to medium-sized water treatment systems. However, it is not suitable for removing suspended biological material. This can be done in an element that combines adsorption with biological activity.

This process combines the use of biological activated carbon with adsorption. The biodegradable organic matter, or biodegradable dissolved organic carbon, which enters with the raw water is transformed into carbon dioxide and biomass by heterotrophic bacteria fixed on the carbon. The biomass is then partially consumed by protozoa. An equilibrium is reached among the inflow of food, bacteria, protozoa and algae. This equilibrium must be carefully controlled in order to assure the quality of the processed water. The granular support and its operating parameters (filtration velocity, contact time and periodic washes) are the only variables that must be controlled to guarantee the optimum biological state of the system.

Figure 4.16 shows a typical chemical contaminant filter system designed for domestic installation. The adsorbent medium most commonly used in such filters is activated carbon. Granular activated carbon adsorption is an accepted method for removing chemical contaminants from drinking water, particularly at the point of use. However, to be effective the flowing water must be in contact with the carbon for a prescribed length of time. To ensure this, pressure regulation and flow control are necessary.

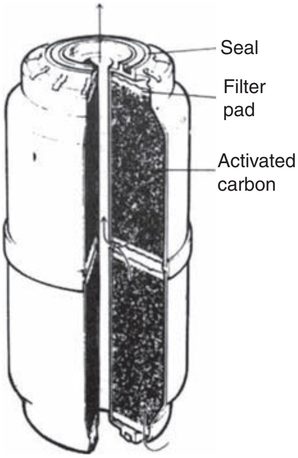


Figure 4.16 Activated carbon water filter

Filter cartridges of activated carbon will contain small amounts of carbon fines. All cartridges should be flushed after installation to remove traces of such fines from the water system before use. Ultra-fine filtering can be combined with carbon filtration to ensure maximum water clarity and maximum adsorptive properties.

There then remains the desirability of dealing with bacteria removed and held in the filter medium. The basic answer is to incorporate an insoluble, non-toxic sanitizing agent in the filter capable of destroying contained bacteria. The bactericide most commonly employed is silver impregnated into the carbon granules, as in Figure 4.17.

4D. PROCESS WATER TREATMENT

In the same way that bulk water treatment may not provide a sufficient degree of raw water purification to satisfy the needs of domestic users, it may also be insufficiently pure for the needs of industrial process operators, whether as input to a steam boiler system, or as a process input itself. There has thus grown up a considerable technology

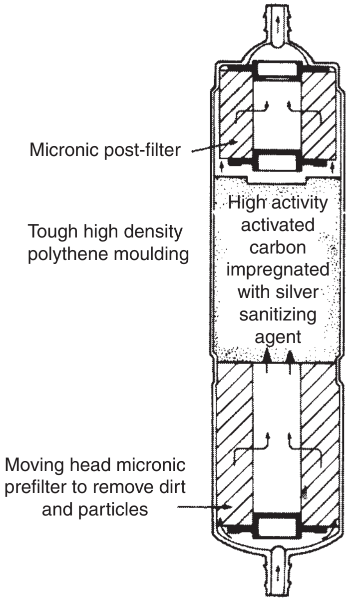


Figure 4.17 Carbon filter with biocide

to purify mains water still further, in some cases as pure as it is possible to make the water with modern equipment and processes.

As will always be the case, the actual purity achieved for a given purpose will be a compromise between the desire for absolute purity and the cost of achieving it. The appearance on the technical scene of membranes first of all, and now microfiltration and ultrafiltration membranes of reasonable cost, has made ‘ultrapure’ water a practical goal.

The processes used to give water this extra degree of purity include filtration, especially membrane filtration, but also include softening, usually by ion exchange, as well as de-aeration and even sludge treatment.

Boiler feed water treatment

Steam is a universal processing fluid, for the generation of electric power, as a heating medium or as a process input. Most boiler circuits involve recycle of some or all of the condensed steam after use. A typical circuit (Figure 4.18) involves:

1. raw or mains water intake, to make up for steam consumed or lost
2. feed water purification, including chemical dosing
3. feed water pumps, creating the steam raising pressure (which can be anything up to and including supercritical pressures)
4. the boiler itself, in which most of the feed water is vaporized on the hot heat transfer surfaces within the boiler

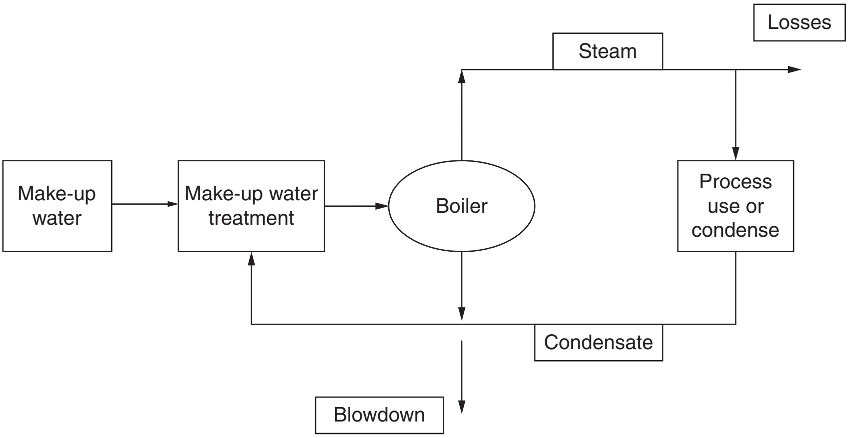


Figure 4.18 Steam boiler system schematic

5. the process in which the steam is used, some being consumed or lost
6. a condenser for the remaining steam, converting it back to water
7. condensate recycle system, returning the condensate to the feed water purification system, and
8. a blowdown system, for draining the boiler.

Apart from the pressure (and temperature) of the generated steam, which may dictate the whole nature of the boiler plant, and certainly will dictate the required degree of purification of the feed water, the most important characteristic of the system is the composition of the make-up water, since this will determine what level of purification will be needed, and what purity of steam is likely to be generated.

The prime purpose of boiler feed water treatment is to protect the boiler, and in particular the heating surfaces, from corrosion and deposition of solids on them – the purity of the steam is largely taken care of by the evaporation of the water, which leaves behind any residual impurities in the boiler. Therefore the treatment processes have to deal with a number of contaminants in the make-up water, and these processes may be either external ones, carried out in the treatment plant, or internal, which conditions the water or steam in the feed lines or in the boiler itself.

The feed water treatment plant has to remove any residual suspended solids in the make-up water, and as much as possible of the dissolved solids. There should be very little suspended material, especially if the make-up water comes from a mains supply, and it would probably be removed in the other treatment processes – so the first step is usually one of microfiltration, as much to keep the passage ways clear in subsequent treatment steps as to protect the boiler.

Dissolved material is much more of a problem, especially if the make-up water is hard. Hardness is a characteristic of groundwater that has percolated through underground strata, dissolving soluble material as it travels. Salts of calcium and magnesium (carbonates, bicarbonates, sulphates, etc.) are reasonably soluble in cold water, but progressively less so as the water temperature rises. As the water is heated in the boiler, therefore, these salts would come out of solution and deposit as scale on the heat transfer surfaces (as in the furring of a kettle), rapidly rendering the boiler ineffective. So hard water must be softened, i.e. the dissolved materials that cause hardness must be removed. For most of the industrial history of boilers, softening was effected by the addition of chemicals that precipitated the calcium and magnesium at ambient temperatures, so that they could be filtered out of the water. This was done in large clarification tanks with reaction chambers at the feed end (reactor clarifiers), followed by dewatering and disposal of the resultant sludge.

By far the most popular method for water softening nowadays is some form of ion removal system, such as ion exchange, electrodeionization or reverse osmosis. It must be remembered that simple ion exchange does as its name implies, that is it exchanges potentially insoluble ions for readily soluble ones (usually sodium), so that the total ion content of the water remains the same, and deposits will still form on the tubes as the water evaporates in the boiler. The safe method of ion exchange is then an acid-base exchange system, which replaces the cations in solution with hydrogen ions, and the anions with hydroxyl groups, i.e. forming a molecule of water for every molecule of metal salt that is removed.

Complete ion removal is also offered by reverse osmosis, in principle, although the permeation of ions through even the tightest membrane is not zero, so there will be a finite, if very low, metal salt content in the purified water. If extremely low salt contents are required, then the most cost-effective method is probably reverse osmosis followed by a deionization process.

The presence of organic materials, especially if the make-up water is from surface sources, will interfere with steam production by the formation of foams. These and other colloidal materials can be removed by ultrafiltration, which will also remove silica, a very uncompromising deposit forming material.

The other major separation task in boiler feed water treatment is the removal of dissolved gases, especially oxygen and carbon dioxide, which will cause corrosion in the boiler. These can be removed by mechanical de-aerators, or chemicals may be added that will scavenge these gases.

Partly because the purification processes are not completely perfect, and partly because of the build-up within the very aggressive conditions of the boiler of solids deposited from solution, it is necessary to drain accumulated solids from the boiler from time to time, in a process known as blowdown, producing a hot sludge to be dewatered and discarded.

In many steam systems, the recycled condensate makes up the largest part of the feed water. The treatment that it has already received makes it a valuable commodity, so it is not discarded, but it must be retreated, because it will pick up some impurities in its flow back to the feed water treatment plant's inlet tank. Condensate polishing may be achieved by a separate ion exchange system, because of the somewhat different requirements.

Ion exchange

Ion exchange processes have been in use for many years to soften water, their disadvantage being that they are batch operations, with a regeneration stage between each softening stage, the regeneration requiring the use of another chemical to restore the soluble ion content of the ion exchange materials.

The basic process involves passage of the feed liquid through packed beds of ion exchange materials in granular form (originally natural zeolites, nowadays synthetic polymers with appropriate ion-bonding structures). By contact with a cation exchange resin, the cations on the resin exchange with the cations in the feed liquid. Similarly feed liquid anions are exchanged on a bed of anion exchange resin. Eventually the beds will become saturated with the unwanted ions, as is indicated by a breakthrough of these ions into the product stream. The feed flow is then stopped, and the bed is regenerated by a flow of liquid carrying the soluble ions in concentrated solution, and the unwanted ions are carried away in the waste from this regeneration stage.

Sensibly, the exchange beds are arranged two in parallel, so that one bed can be run with raw water feed, while the other bed is being regenerated, their respective functions being interchanged as the first becomes saturated. As foreign matter in the form of suspended solids would interfere with the ion exchange process, a fine filter is usually mounted ahead of the beds of resin.

The standard water softening ion exchange system uses cation resins only, to exchange soluble ions such as sodium for the hardness-causing calcium and magnesium. The system then uses salt to supply the regenerating ions, which is generally satisfactory where sodium's presence in the product water is acceptable. However, this softening process does not change the number of dissolved ions, and where a reduction in dissolved material is required, as in high quality boiler feed water, complete deionization (as shown in Figure 4.19) must be used, with a strong acid cation bed,

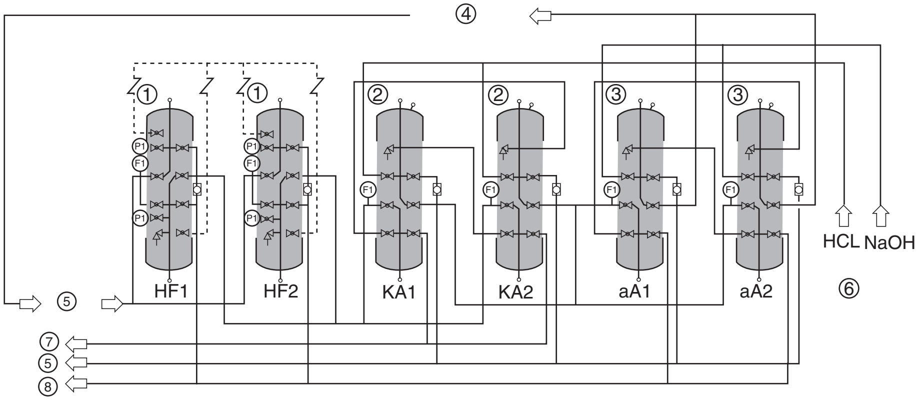


Figure 4.19 Deionization plant. 1, Multi-media prefilter; 2, cation exchanger; 3, anion exchanger; 4, process water; 5, raw water sump; 6, regeneration chemicals; 7, acidic waste; 8, alkali waste.

exchanging hydrogen ions for the incoming cations, and a strong base anion resin, exchanging hydroxyl ions for the incoming anions. Figure 4.19 shows a system with each unit in duplicate, including an influent sand filter. A system like this produces a reasonably strong acid waste, and a corresponding alkali waste, which must both be neutralized before disposal.

Ultra-pure process water

Not only boiler feed, but a wide range of other applications require a high degree of influent water quality, much purer than available from mains water distribution. In the electronics industry, components (especially semi-conductor materials) must be washed in water that is sufficiently pure as to leave no residue behind after the washing process, even from evaporated droplets. The pharmaceutical industry needs pure water as a base for growth cultures, as a constituent of parenteral drugs or many other types of medicine, which is guaranteed to be free of pathogens or any other micro-organisms, which occur in sizes well below 0.1 µm – a condition that relates especially to the biotechnological component. The cosmetic and toiletries sector uses water as an ingredient for the majority of its products, and demands absence of colour and dissolved materials as important conditions in its feed water. Similarly, many parts of the food and beverage industries demand highly pure water as an ingredient, as do many sectors of the chemicals industry.

The qualities that determine the suitability of a feed water include the absence of suspended particulate material, determined by microscopic examination and/or membrane filtration, and the absence of dissolved material, especially organic colour and mineral salts, determined by visual observation and electrical resistivity measurements.

The optimum process for ultra-pure water production combines membrane separations and deionization processes, and the combination can be tailored to meet the required purity of the product water. Microfiltration would be the first stage, to remove much of the residual suspended material and most bacteria. Ultrafiltration can then be used to remove viruses and other pathogens, large organic molecules, colour and other colloidal material. A deionization process using acid-base ion exchange can finally be used to remove all remaining dissolved material, although a reverse osmosis process can also do this, and a combination of these last two processes may provide the best solution.

Membrane processes

The availability of inexpensive membrane materials has revolutionized pure water production, and provided one of the largest markets for such materials. There is now a relatively straight trade-off between the desired purity of the product water and the money available to achieve that purity.

There are four main processes utilizing membranes for the separation of impurities from water. Two of these, microfiltration and ultrafiltration, as their names imply, work by a filtration process, i.e. they present a porous barrier to the flow of a suspension of solid or semi-solid material, which allow some of the solid to pass through the barrier, entirely according to the size of the suspended material. The other two membrane processes, reverse osmosis and nanofiltration, do not have physical holes in their structure, but work by diffusion, i.e. the species to which the membranes are permeable move at the molecular scale through the structure of the membrane.

Their separation functions overlap to some extent, although the centre points of their working ranges are quite distinct, as shown in Figure 4.20. The processes are differentiated by their range of separation cut-points and normal duties:

reverse osmosis: 25 to 300 Daltons, retaining quite small molecules, small ions
nanofiltration: 150 to 15,000 Daltons, retaining somewhat larger molecules and most ions
ultrafiltration: 5000 to 200,000 Daltons or above (up to 0.1 μm), retaining large organic molecules and colloidal solids
microfiltration: 0.05 to 3 μm or above, retaining fine solid particles

The different cut-points are directly related to the driving pressure required to achieve them. While most microfiltration and some ultrafiltration need little more

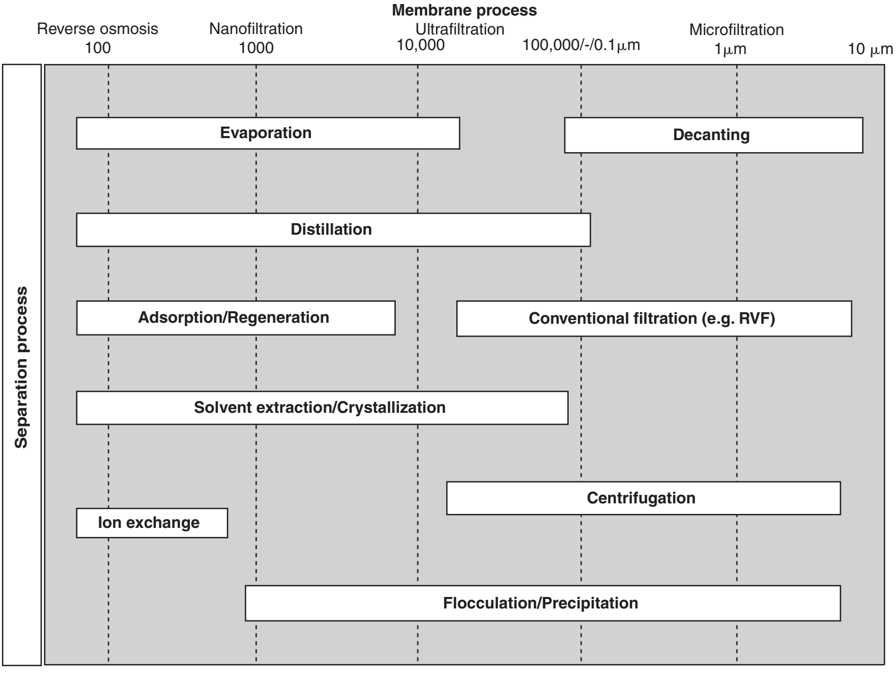


Figure 4.20 Working ranges of membrane and other separation processes. Note: Numbers without units at top of chart are approximate molecular weights, in Daltons

than 1 bar of transmembrane pressure, reverse osmosis processes may require as much as 50 or 60 bars. Clearly reverse osmosis becomes an expensive process to operate at this level, but it is still the best way to achieve ultra-pure water, when coupled with a deionization system to remove the ions that get through the reverse osmosis membrane.

Continuous electrodeionization technology uses mixed bed ion exchange resins and selectively permeable membranes to extract dissolved salts from water under the influence of an electric field. This field drives the ions away from the products flow and continuously regenerates the resin beads, avoiding the need for chemical regeneration. The combination of reverse osmosis and electrodeionization is claimed to be the safest and most reliable way to produce purified water.

It is very important to remove suspended solid particles ahead of membrane processes, especially those using hollow fibre or spiral wound modules, or the particles are likely to block the narrow flow passages. For large flow rates, a suitable filter for this purpose would be a deep bed filter, whereas for smaller flows, polishing cartridges with pleated or thick media can be used.

The normal chlorine treatment of water kills bacteria and fungi to a large degree, and a prefilter and reverse osmosis complete the process. However, bacteria thrive on the resins used in ultra-pure water systems, requiring that the systems be sterilized periodically. In between sterilizations, cartridge polishing filters can be used to trap any bacteria remaining in the system. Decaying vegetable and animal matter release long chain organic molecules into municipal water supplies, of which most are removed by a reverse osmosis system. In extreme cases, special resins and activated carbon beds may also be required.

Ultra-pure water is quite corrosive and it attacks the transport lines, valves and other system components, producing particulates downstream of the polishing filter. A point-of-use filter rated at 0.2 µm or a small ultrafiltration system should therefore be used. The complexity thus implicit in an ultra-pure water system is illustrated in Figure 4.21, which also shows a recycle stream of used wash water.

The most important performance characteristics for final filtration cartridges used in ultra-pure water production are as follows:

- the minimum possible migration of particulates and ions from the cartridge itself (fibre releasing materials must not be used in these filters)
- lowest possible initial pressure drop, since pressure drop in the filter system represents lower pressure availability at the point of use
- highest throughput for maximum economy, and
- quickest rinse-down after cartridge change, to minimize waste of water and time.

4E. MUNICIPAL AND INDUSTRIAL WASTEWATER TREATMENT

The treatment of wastewater is as large a process, at least in liquid volume terms, as the provision of fresh water. The water abstracted for domestic, commercial, institutional and most industrial uses is largely returned to the environment as a waste,

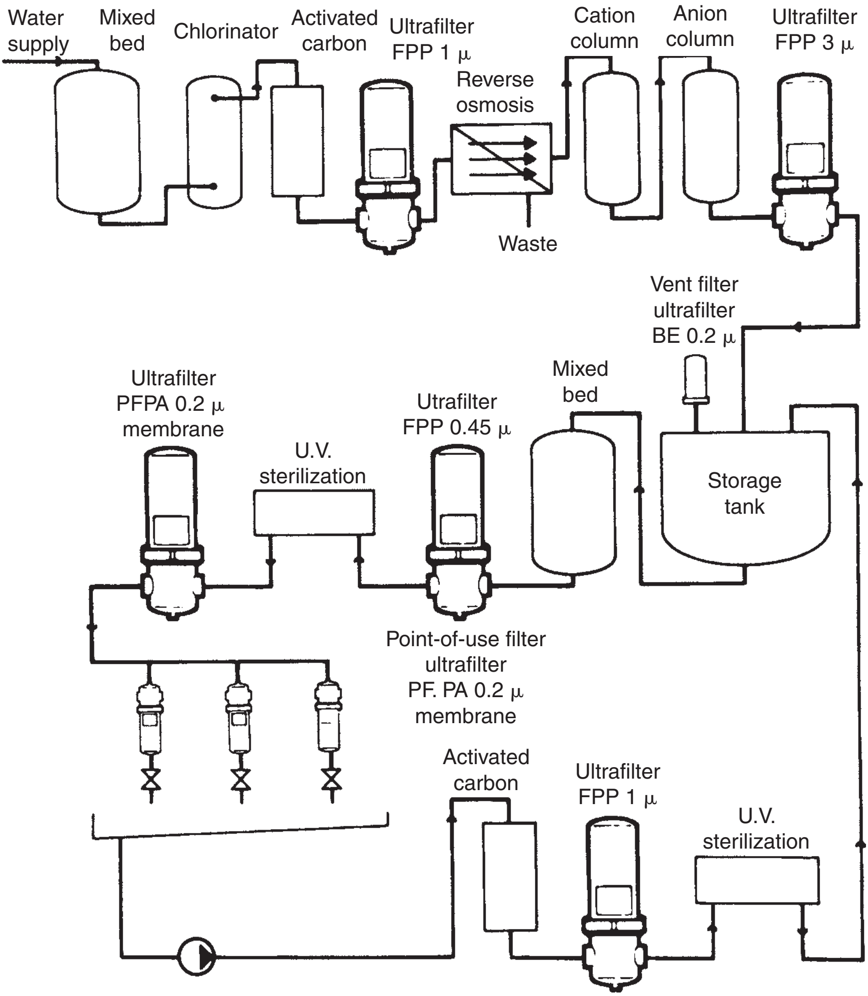


Figure 4.21 Ultra-pure water production schematic

in need of treatment before it can be safely discarded. Wastewater treatment is a vital process in the context of sustainable existence, and is a huge application for filtration and related equipment.

In the majority of developed areas, municipal sewage treatment means the purification of wastewaters coming from domestic, institutional, commercial and industrial activities, combined with street and other hard surface run-off, all carried by a sewerage system and delivered to a treatment works owned by the municipality or by a private operator. Its objective is to convert this mixed waste into a treated liquid effluent that may be safely returned to the natural environment. Untreated sewage, on discharge to a watercourse for example, would consume oxygen, thus killing plant and animal life, and it would also cause a nuisance, as well as being a hazard to human health.

Industrial wastewater treatment has many features in common with the municipal process, but usually has an extra step to take care of the particular features of the industry from which the waste has come.

Municipal wastewater treatment

The treatment of municipal sewage is one of the few processes in commercial life where the managers of the appropriate processing plant have little or no control over the quality of the material coming to the process. The treatment plant must therefore be able to cope with a wide range of flows, containing a wide range of impurities. These impurities will be both suspended and dissolved, organic and inorganic, benign and toxic, and the treatment works must have in place decontamination processes that can reduce all of these impurities to below a set of limits defined by national and local regulatory bodies. These limits will vary according to the nature of the recipient body of water. If this is large, fully oxygenated and fast moving, then less purification is necessary than where the recipient is an important local amenity, or supports a fish farm, or where the discharge point is upstream of a major water abstraction point.

In addition, of course, to the purification role, the treatment plant is producing a valuable product: clean water, as well as a solid by-product that, by proper processing, can also be made to yield usable products, even if only as the energy recovered from its incineration. Almost all of the fresh water, drawn in to the domestic, commercial and industrial processes from which the waste comes, is rejected by these processes to the local sewer, and is there supplemented by the rainwater running off from the neighbourhood.

Treatment processes

Sewage treatment thus involves the reduction in concentration of suspended (insoluble) and dissolved impurities to required levels. The overall process is characterized by some important features:

- the quantities involved are very large (they are often measured in ‘population equivalents’, where waste production is of the order of 150–200 litres per day per capita for domestic wastes only, with at least as much again from other sources)
- the concentration of impurities in the influent sewage, under normal conditions, is actually quite low (0.5% of suspended solids and 1% of dissolved organics are quite high figures), and
- the concentration of impurities can vary very widely, even from hour to hour (while a large rain storm can make a tremendous difference).

Municipal treatment has been developed over a very long period, and was basically codified by the Royal Commission into Sewage Disposal (working from 1898 to 1915). From the investigations of the Commission the two-stage treatment process became established as the satisfactory method of achieving a purification good enough for the intended disposal route.

Considerable development of the treatment process has occurred over the last few decades, mainly to improve the efficiency of the two-stage process, but also to introduce a third stage where disposal needs required it, and to reduce energy demands, taking advantage of parallel developments in equipment and processing techniques.

The standard process begins with the *primary* stage, which involves the removal of suspended solids that can be separated easily, by screening or sedimentation. These solids are then treated separately from the main process line, to render them fit for safe disposal.

The settled sewage from the primary stage passes to the *secondary* stage, which deals with residual suspended material and the bulk of the dissolved material by an aerated biological digestion process. This is followed by a second stage of settlement to separate the sludge resulting from this secondary treatment, which is also removed for separate treatment and disposal.

The clarified effluent following secondary treatment may be clean enough for discharge to a water course, or it may need still further treatment, in a *tertiary* stage, for a variety of polishing processes to suit the effluent discharge requirements. There may well then be some tertiary sludge, also needing disposal.

Each of the above processes is carried out in a range of equipment, most of which is part of the filtration process spectrum. There is very little overlap among the treatment processes, although some newer processes combine more than one stage in a single process. Accordingly, the equipment items used in each are fairly distinct.

Primary treatment

The removal of suspended solids is usually achieved in three processes, an inlet screening, followed by two stages of sedimentation. The influent sewage carries with it a wide range of solid objects that are put into the sewage system or that fall into it, such as dead animals, rags, sticks, human waste, and so on. These objects may be floating or suspended in the flow, so the incoming flow must be put through a screen to remove the larger objects, to prevent their causing a blockage or damaging equipment further into the process.

These larger suspended or floating objects are removed in a full-flow screen, through which the whole sewage flow passes. This can be a vertical bar grate, which is scraped clear of trapped solids on a regular basis, or a moving screen that transports the collected material out of the liquid flow.

The sewage then passes through a grit trap, in which the flow velocity is adjusted to allow the settlement of inorganic sand and grit particles (that are mostly swept along from roads and roofs by stormwater), but not the softer and less dense organic particles, which are carried through this trap. As most organic material does not settle with the grit, this can be scraped out of the trap, washed and sent to landfill.

With large objects and easily settled solids removed, the flow rate of the sewage can now be measured (perhaps by a notched weir) as a guide to how downstream processes should be set, but also as in indication of a storm-driven surge in liquid flow. Under the circumstances of a storm surge, most works will have storm tanks awaiting this eventuality. Some of the main flow is then diverted into temporary storage in the tanks, and released slowly back into the main flow once the storm is over. These tanks will have to be designed recognizing that there will be suspended organics in the diverted water, and these must not be allowed to build up in the storm tanks.

The third primary process is a settlement stage, in which the sewage is held in large open tanks, with a gentle liquid motion in them, which will allow the settling out of the heavier organic solids. They are also designed with grease traps at their tops to remove floating fats, oils and grease. The organic content of the sewage is reduced by 25–50% in this sedimentation process, and a considerable amount of primary sludge is accumulated, which must be removed regularly, if not continuously.

The grit trap and primary settlement system are both sedimentation devices, the first with quite a high liquid flow, sufficient to allow the dense sand and grit to settle, but to retain the lighter organic material in suspension. The majority of the suspended organic matter is then removed in large settling tanks, in which the solids fall to a sloping floor and the clarified liquid flows out over a weir at the top of the tank and then under a grease trapping baffle. The solids on the bottom of the tank are raked to a central point (in a circular tank) or to one end (of a rectangular tank) and discharged as a thin slurry. Such a clarifier takes up a large ground area, but a more complex design is available (Figure 4.22) using a lamella separator system, with a much smaller footprint.

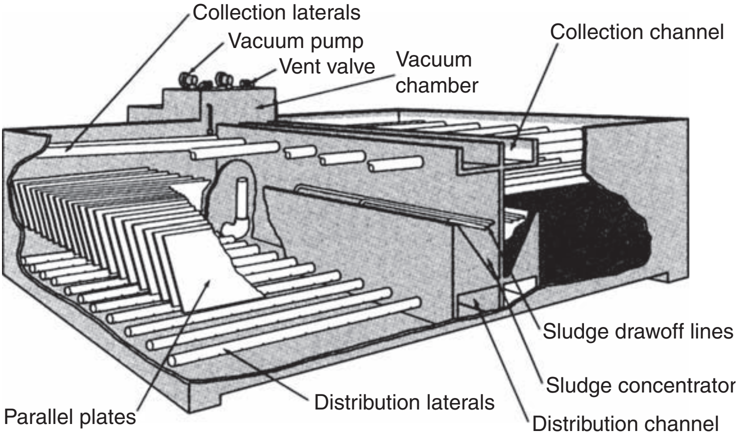


Figure 4.22 Primary lamella clarifier

Secondary treatment

The secondary process treats the residual organic material, both suspended and dissolved in the sewage, by reacting it with aerobic bacteria in an aerated system, so that the bacteria digest the organics and oxygen, growing in the process. This is a time-related process, with a more complete digestion occurring the longer the reaction is allowed to proceed. It is, however, brought to an end after an optimum reaction time dictated by the effluent quality needs of the treated sewage to be discharged. The generated bacteria are then separated from the treated liquid by sedimentation, leaving an effluent capable of being discharged to all but the most sensitive waters.

The first stage of the secondary treatment process is intended to bring the settled sewage into contact with active bacteria and oxygen as efficiently as possible to allow the digestion of the organic content. In older and smaller works this is done in a 'trickle filter', which is not a filter at all, but a packed bed of inert material over which the settled sewage is caused to flow and trickle down from one piece to another of the packing, mixing with air as it does so. Very quickly a biological film grows on the packing and the contact with the bacteria starts the digestion of the sewage organics. The established film continues in use for a considerable time. As the film grows by means of the digestion process, surplus bacteria break way as solids to be separated.

Most large works now use the activated sludge process, in which a mass of aerobic bacteria is suspended in a tank full of settled sewage, which is agitated by streams of air bubbles. The residence time in the tank is quite long, normally several days, during which time the organic content is largely removed. The tank is effectively a sedimentation vessel, but with the system parameters such that the biomass is kept in suspension.

The suspension coming from the underdrains of the trickling filter, or the overflow from the activated sludge tank, is settled in a secondary sedimentation tank, the clear effluent being discharged if clean enough, and the separated sludge being sent for disposal (although a fraction of the activated sludge is recycled to the head of the activated sludge process to maintain the active bacteria stock in the reactor).

Tertiary treatment

Where the effluent quality after secondary treatment is not good enough to be discharged, then some kind of tertiary treatment will be required. This may be to polish the effluent by removing the last traces of suspended solids. It may be to remove some more of the nutrients nitrogen and phosphorus that would promote unwanted plant growth in the recipient water. It may be to remove more organic material from solution. Or it may be to do all three, but whichever, then there will normally be a final stage of disinfection to destroy viruses, bacteria and other harmful micro-organisms.

The main tertiary treatment process is then a filtration one, using either a sand bed or a membrane process, usually microfiltration, possibly followed by ultrafiltration. There may also be too high a content of nitrogen and phosphorus, and this will require additional biological processes, with some more sludge to be separated.

Sludge processing

The various stages of sewage processing each produce a sludge in which the wastes from that stage are concentrated, although, of course, in much smaller volumes. These sludges must all be discharged, eventually to the environment, but in as safe a manner as possible.

The primary screenings are capable of decomposition and so need very careful handling. They may be compacted and sent to landfill, or macerated and added to the primary settlement solids. The mineral matter from the grit trap is relatively clean, and is sent safely to landfill. The primary and secondary settlement sludges are considerable in quantity and are relatively thin (dilute), so that the quantity to be disposed of is high. They are therefore dewatered mechanically before shipment to landfill or use as a soil improver or incineration. Tertiary sludges will vary in composition according to the nature of the process producing them, but they will probably all need dewatering before final disposal.

A major process for the treatment of sewage sludges is their decomposition by anaerobic digestion, at temperatures somewhat above ambient, with methane as a by-product. The sludge quantity is roughly halved by this means, the residual sludge being more easily dewatered, and a useful fuel is generated as well.

The various sludges arising from sewage treatment will be highly organic in content, and will need extensive dewatering to render them fit for their final disposal, even if this is just to be incinerated. This is a major treatment works task, involving filter presses, or horizontal belt filters, or decanter centrifuges, with filtrate or centrate recycled to the start of the works. Even if the sludge is digested first, there is still a considerable degree of dewatering required of the resultant sludge.

Process alternatives

There are many alternatives to the direct line of treatment processes described in the preceding paragraphs. One such takes the whole sewage, before primary settlement, and treats it at above ambient temperatures with anaerobic bacteria, to produce methane and a benign liquid effluent and separated sludge. This process has many advantages, but is not yet accepted as a satisfactory answer to the sewage problem.

Most alternatives apply to the secondary process, including the use of rotating biological contactors (discs carrying the aerobic bacteria), and the sequencing batch reactor (which combines secondary treatment and sludge separation). The most exciting development, of considerable interest to the filtration industry, is the membrane bioreactor (MBR), which uses a membrane to separate the clean effluent from the activated sludge zone.

The MBR uses microfiltration membranes, or loose ultrafiltration membranes, to separate clean water from the activated sludge broth. The membranes take the form of a module of either hollow fibres or flat sheets, and they operate at low transmembrane pressures, being driven either by suction, or hydrostatic head, or by a low system pressure. The module may either be submerged in the activated sludge suspension or be housed in a separate vessel. The MBR replaces the secondary activated tank of the conventional system, including its settlement zone, and takes up considerably less area in doing so. It can also cope with more suspended organics in its feed, so it reduces the size of the primary settlement system as well. Air streams through the MBR serve both to aerate the sludge and to scour the membrane surfaces.

Industrial wastewater treatment

Industrial wastes differ from municipal wastes in three main respects: they are usually much stronger in waste material content (both inorganic and biodegradable); they are often acidic or alkaline in nature rather than neutral; and they frequently contain highly toxic materials. The presence of oils, either as droplets or as an emulsion, is also a problem with much industrial waste. On the other hand, the wastes coming from a particular factory are usually fairly constant both in quantity and composition.

The annual cost of treating industrial wastewater and its resulting sludges is huge, but is still far below the level needed for good health around the world. There is comprehensive legislation in place in most industrialized countries governing the discharge of wastewater from industrial sources, yet pollution from such wastewater coupled with poor wastewater treatment remains a major concern for the whole world. Despite the relatively strict enforcement of the appropriate regulations in many countries, many industries are still failing to regard wastewater seriously, often through ignorance of the regulations and a lack of basic understanding as to what kinds of wastewater treatment technology are available. Wastewater treatment is thus a complex task for environmental management.

Most industrial wastewater treatment plants are in two major sections: the first to deal with the particular product of the factory, and the second to deal with the general wastes, and perhaps the effluent from the first stage, which uses the same general scheme as that for municipal sewage. The main function of the first stage is, or should be, the minimization of the loss of any product material in the waste, i.e. it should be regarded as a material recovery process rather than as waste treatment. This may be quite a complicated process, as shown in Figure 4.23, which illustrates a waste treatment plant for a vehicle dewaxing process, designed to recover the dewaxing solvent and produce a water that can easily be treated by a conventional two-stage process.

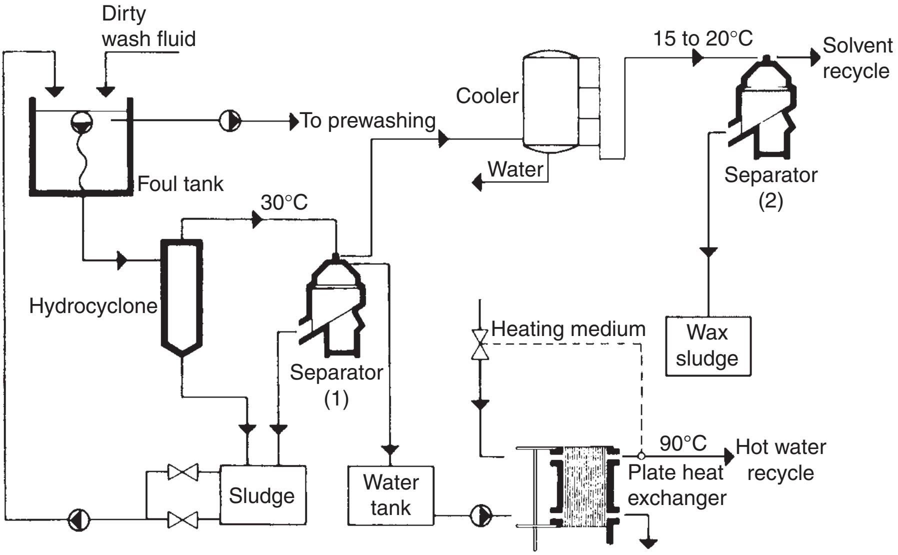


Figure 4.23 Dewaxing waste treatment plant

A general guide to the methods used for the specific industrial waste treatment stage is given in Table 4.2. Obviously, if more than one type of contamination is present, then treatment appropriate to each will be required.

Table 4.2 Industrial wastewater treatment

Contaminants and/or problem	Suggested treatment
Oil in globular form	Gravity type settler with oil skimmer
Oil as emulsion	Coalescing separator, ultrafiltration
Large solids, no fines	Rotating screen
Easily settled solids	Gravity separator, possibly with flocculation
Fine suspended solids	Bulk clarifier, with flocculation
Slurry or sludge	Vacuum drum filter, belt filter, decanter centrifuge
Dissolved organics	Bacterial digestion, membrane filtration solvent extraction
Dissolved inorganics	Chemical reaction to precipitate solubles, then filter Membrane filtration, especially if solute is valuable
pH adjustment	Dose with acid or alkali as appropriate

The presence of oil in wastewaters is common – and methods of dealing with it are illustrated later in this Section (and also in Section 5). The other main problem with industrial wastewater is dissolved material, whose concentration is above the levels permitted in discharges across the factory boundary. For organic materials, which are not wanted, digestion with specific bacteria may be the best solution, although a final pass through the equivalent of an activated sludge system may still be required. Membrane filtration, especially ultrafiltration, will separate most organic materials without destroying them (although producing a concentrated organic waste if the materials are not wanted), while solvent extraction can be used to recover specific organic materials.

The recovery of dissolved inorganic materials can be achieved by evaporation and crystallization, although membrane filtration is probably a more economic process. If the materials are unwanted, then membrane separation will still remove them from the liquid wastes, but only as a concentrated solution, still in need of treatment. Chemical reaction, probably also involving pH adjustment, to convert the dissolved salts into an insoluble precipitate, is an attractive treatment process, with filtration of the precipitate from the resultant suspension.

Figure 4.24 is a schematic flow sheet for a continuous reaction and dosing plant for the removal of waste inorganics. The raw waste is accumulated in a collection sump (1) and then pumped through a series of reaction tanks (2–4) whose functions may be neutralization, precipitation, and flocculation of the precipitated solids. The resultant slurry is settled in a clarifier (5) from which the clarified liquid flows on (8) to discharge if clean enough, or to a polishing filter or a general sewage treatment works. The sludge from the clarifier is thickened (6) and then dewatered in a filter (7) or decanter centrifuge, with the filtrate joining the clarified liquid flow (8) (or being returned to the clarifier).

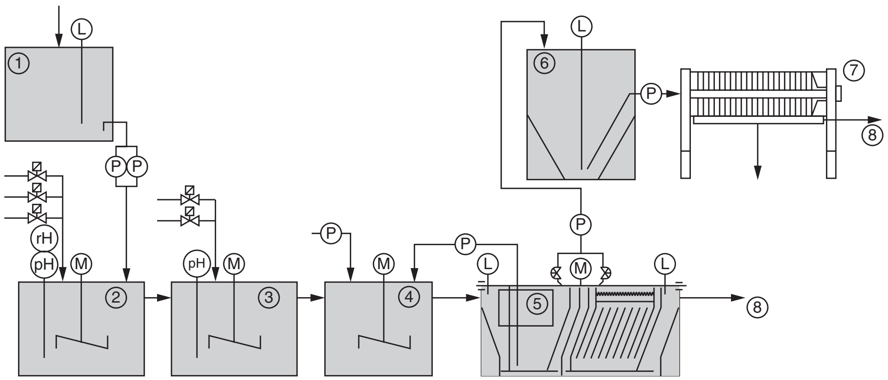


Figure 4.24 Chemical reaction plant. 1, Collection sump; 2, Treatment tank; 3, Neutralization stage; 4, Flocculation stage; 5, Compact clarifier; 6, Sludge thickener; 7, Filter press; 8, Final filtration step.

4F. PROCESS FILTERS

It was stated earlier that industrial filter applications can be divided broadly into two groups, those providing a service to a factory operation, the utility filters, and those acting as a main production unit, the process filters. It was further stated that the utility filters were largely concerned with clarification of a fluid, and so with system protective and contamination preventive duties, and that this Handbook is primarily concerned with this type of filter, which, on the whole, is a small device.

Nevertheless, for the sake of completeness, if nothing else, some mention must be made of the range of process filters, as has been done in Section 3, to be supplemented here with notes on some process applications, largely for the cartridge and membrane filters mainly associated with utility duties. Membrane processes are increasingly finding application in a wide range of processes, including:

- purification of water and feed materials
- purification of solvents
- elimination of solvent-using processes, thereby increasing intrinsic process safety, and aiding the drive towards environmentally friendly processes
- increasing product yields
- continuous removal of reaction products, to increase the rate of reaction (as in membrane reactors)
- recovery of catalysts
- purification and concentration of low molecular weight organics
- separation of reactor by-products as purified streams
- separation of liquids from reactions such as dehydrogenation, oxidation, esterification, etherification, and dehydration, and
- concentration of slurries and suspensions.

Some typical industrial membrane elements are illustrated in Figure 4.25, which shows pleated sheet membrane and lenticular elements.

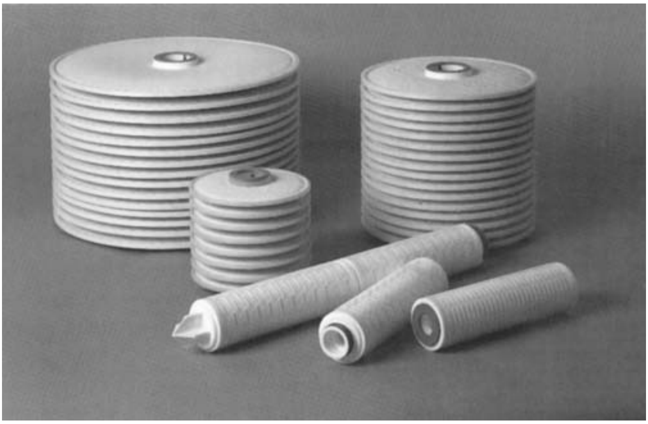


Figure 4.25 Industrial membrane elements

Spirally wound membrane modules can generally meet most process application requirements. They are particularly suitable for sanitary applications in the pharmaceuticals, biotechnology, dairy, food and beverage industries. They are also widely used in the industrial sector for environmental protection, metal coating, chemical and paint applications.

Hollow fibre membrane modules are more suited for applications that require high packing density and high purity. Typical areas of application include wine filtration, and pure water production for pharmaceuticals and electronics, as well as surface water treatment and use in a membrane bioreactor.

Multi-tubular membrane modules are best suited for feed streams with higher levels of suspended solid content, such as sludge concentration in wastewater treatment, degreasing plant bath life extension, oily wastewater treatment and paint recovery.

In the processing industry in general, a well-designed filtration system must remove the contaminants within specified limits, and must continue to maintain the quantity of filtered solution over the service life of the filter. A properly sized and well thought out filtration system can save headaches as well as money. An oversized system wastes filter medium, especially if this needs changing frequently for other reasons, and involves investment in unnecessary hardware. An undersized system does not perform as efficiently as expected and requires premature replacement of the filters. System sizing is best carried out by a trained applications specialist, who may use several methods to make a determination of the specific needs of the process that maximizes filter performance.

Vacuum process filters

Rotary vacuum drum and vacuum belt filters are extensively used on many process filtration operations, to provide filtration, clarification, dewatering or concentration. Moulded thermoplastic vacuum drum filters are particularly suited to providing continuous filtration of corrosive chemicals, without using expensive or hard to obtain exotic metals such as titanium, stainless steel, monel, Hastelloy or rubber covered steels.

Belt press filters for dewatering have found favour in the broader mineral, chemical and metal processing industries, including the treatment of coal refuse, gold and silver tailings, aggregate washing, dewatering of wastewater treatment sludges (primary sludge, waste activated sludge and anaerobically digested sludge), and pulp and paper sludges. Solids must be sufficiently dewatered before being subjected to compression pressures or extrusion from the edges of the belts will occur. This is usually accomplished by a gradual increase in pressure over a fairly long dewatering zone before the solids are finely squeezed between the belts to remove the remainder of the liquid.

Horizontal belt vacuum filters have the advantage of fast filtration cycles, flexibility of operation with either co-current or counter-current washing, and generally low maintenance costs. Typical filtration areas are from 1 to 140 m^2, with processing capability ranges from a rate of 50 to 9800 kg/hm^2 depending on the filterability of the material.

Capillary disc filter

An interesting extension of the range of vacuum filters is the capillary disc filter (Figure 4.26). This is a continuously operating, capillary action, ceramic dewatering filter, which eliminates the need for separate filter cloths. The filter medium is a disc, formed from two circles of sintered alumina, joined at their circumferences. The filter has several such discs mounted on a central horizontal shaft. The medium is practically inert in most solutions, and may be used in a broad range of water-based and solvent-based slurries. In operation, as the microporous ceramic discs rotate through

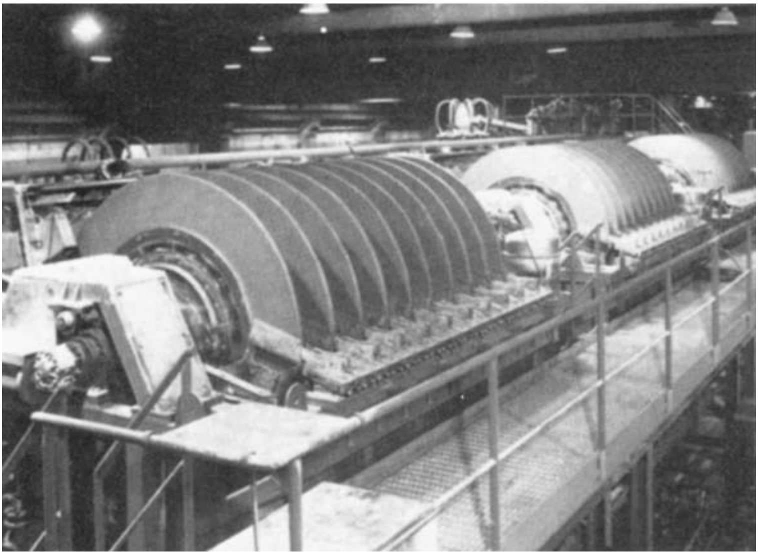


Figure 4.26 Capillary disc filter

the feed slurry, capillary action and an almost complete internal vacuum draw liquid through the medium to the inside of each disc.

Some liquid is retained in the micropores as a result of surface and interfacial tension effects, preventing either air or solids from passing through the medium, and resulting in the solids building up as cake on the outside of the discs. The filter cake has an extremely low moisture content. Scrapers remove the cake leaving a thin coating on the disc surface, which acts as protection against mechanical abrasion. Filtrate is then used to flush the plates removing the residual heel in a backflow washing process. Typical filtration area for the capillary disc filters ranges from 5 to 45 m^2, and the number of discs can be from 6 to 20 or more.

Electronics industry

The critical applications in the electronics industry are the production of ultra-pure water for the washing of semi-conductor material (silicon chips), and the cleaning of the chemical fluids (liquid and gaseous) used in their manufacture. The object of an ultra-pure water plant for semi-conductor manufacture is to produce water as close to the theoretical purity as possible. Users of ultra-pure water should take all steps possible to ensure that the filters selected meet the highest standards of quality and performance. Every fluid that comes into contact with integrated circuit surfaces is a potential source of the contamination that will affect yields. For this reason, filtration of these fluids at the point of use is essential to obtain high yields. All chemicals that contact microcircuits should be filtered to a level of at least 0.2 μm.

As integrated circuit fabrication advances into the very large-scale integration (VLSI) range, the effect of contaminants on yields becomes of paramount importance. In 1977, an impurity level of 10 particles/ml was acceptable, but nowadays a level significantly less than one particle/ml is sought. Fluids with higher levels than one particle/ml can be very damaging: one defect/cm^2 on a VLSI wafer can potentially cause a greater than 80% yield loss per wafer.

The sensitivity to contamination of an integrated circuit increases as the geometries shrink. Particles as small as one tenth of the size of the minimum wafer geometry can cause a defect in the device. This means that, for VLSI geometries, particles of 0.1 μm are potential source of defects and are therefore of much concern. Particulates in fluids can produce various types of defects in a semi-conductor device, including holes, gaps and bridges, or leave additional elements on diffusion. If particles are caught between oxide layers, they can lead to cracks and eventual failure of the device.

The source of these contaminants is the fluids that come in contact with the surface of the wafer during the various process steps. These fluids include water, reactive chemicals, gases and photoresists, all of which are used in device fabrication. In these fluids there is a wide variety of undissolved solids (particulates), which include polymeric colloids, colloidal silica and iron, glass particles, fibres and metallic and airborne particles. The levels at which these particulates affect the fabrication of the device depend upon the device itself, its geometry and the chemical process used.

The acceptable level of particulates also depends upon particle size, particle type and the procedure for counting the particles. For example, the large particles that are simple to remove and are easily and accurately countable should not be present at all, while smaller innocuous particles less than 0.2 μm in size can exist in substantially higher relative numbers without affecting the yield of some devices.

As a rule filters must be sized so that the maximum amount of filtration can be carried out in the smallest possible housing, with the highest surface area per cartridge within the housing. Filter cartridges should have a large surface area, a high flow rate and a low pressure drop. Another way of stating this requirement to optimize particle and contaminant removal is that the fluid face velocity (volume per unit area filtered) should be minimized. For example, the face velocity for liquids should be kept to less than 0.8 $l/s/m^2$ of membrane area.

The production process for wafers includes marking their surfaces with the circuits required in the form of photoresists, etching the surface where it is not protected by the photoresist, and washing it after every process stage. This wash water is the one that needs to be ultra-pure, and a typical analysis for such a water is given in Table 4.3.

Table 4.3 Wash water specification

Resistivity	18 megohm/cm at 25°C
Sodium	Maximum 0.1 ppb
Potassium	Maximum 0.05 ppb
Zinc	Maximum 0.02 ppb
Iron	Maximum 0.02 ppb
Aluminium	Maximum 0.2 ppb
Silica as SiO_2	Maximum 0.5 ppb
Chlorides	Maximum 0.05 ppb
Particles 0.5–1.0 μm	<50/litre
Particles 1.0–2.0 μm	0
Total organic carbon	<50 ppb
Living organisms	<1/ml

Etchants

The chemicals utilized for etching are aggressive acids, such as hydrofluoric, nitric and phosphoric. Other chemicals are used to clean the surface of the wafer, preparing it for the next stage in the fabrication process. All of these chemicals are potential sources of particulate contamination. With respect to etchants there are two major sources for particulate contamination: the etching process itself and those sources associated with the delivery of the acid to its point-of-use.

By its nature etching is a self-contaminating process. During etching acids react with thin film material exposed on the wafer and remove this film from the surface to create a pattern in the film as defined by the way that the photoresists were laid down. This process can generate particles, inorganic colloids and reaction residues.

The second source of particulate contamination is the acids themselves, as they are received. These acids are the most likely of all process fluids to contain damaging particles. Contamination levels as high as 100 million particles per litre, derived from storage containers, sinks and process equipment, are possible.

The thin films used in electronic device fabrication can have a thickness in the range of 0.02 µm (200 Å), which means that sub-micrometre particles can have a disastrous effect on device yields. In fact, particle generated pinholes in thin gate oxide films are one of the major causes of low yields in most integrated circuit production.

Metallic impurities (colloids and particle) are of special concern because of their ability to be readily incorporated in exposed areas by substitution in the crystal lattice, or by being chemisorbed to active surfaces. Wafer surfaces are especially vulnerable to chemisorption during the etching and cleaning processes. Acids utilized for these processes continually generate chemically active and reactive surfaces.

Filter specifications

Filters for applications in etching processes are required to be capable of withstanding a broad range of aggressive chemicals, from strong acids to strong bases or strong solvents. The filters must exhibit low levels of extractables under the operating conditions of this broad range of chemicals, and must not be susceptible to releasing fibres. The filter itself should be self-wetting for easy handling.

Since the etching process is itself a source of particulate contamination, the etchant solution must be continually filtered. Such immersion processes must allow contaminant-free acids to be recirculated and employ membrane filtering at the point-of-use. Recirculation ensures continual sub-micrometre cleaning in order to minimize attachment of harmful metal-containing particles and colloids to the active wafer surfaces that are created by the etching process. The filter utilized in this process should have a cut-point of 0.2 µm. Traditionally, PTFE has been used for the actual filter medium, although polypropylene material is gaining in popularity.

Gas processes

The use of gases in integrated circuit fabrication is increasing, particularly with VLSI technology. This technology is demanding more and more dry processing in order to achieve sub-micrometre geometries. These dry processes are, for the most part, based on the use of gases as reactants. Thus, there is an increasing dependence upon clean, dry, particle-free gases. Gases are used at various stages of fabrication, including the growth of polysilicon and epitaxial layers, the generation of a variety of chemical vapour deposited (CVD) thin films, the development of oxide films, and the etching of thin films with plasmas.

Particulates in gases can be generated from the movement of mechanical parts such as regulators, valves and flow controllers, or from copper plumbing, corroded pipes, solder debris, rust in gas lines, fibrous filters and foreign powder precipitates in cryogenic or ambient gas storage cylinders. Another source of particulates in gases is inherent in the manufacture or separation of the gases. Throughout the processes that utilize gases, the semi-conductor devices are exposed to these particulates. They often can be seen as bright speckles of ‘moon dust’ on the wafer surfaces under high intensity reflected light.

The elimination of particulate impurities in gases is critical in order to prevent the introduction of these impurities into vapour-deposited thin films, silicon substrate surfaces and silicon crystal lattices. Incorporation of gas-derived particulates and metallic contaminants often leads to crystallographic defects. These defects can be manifested in stacking faults, dislocations and metal precipitates, all of which could alter diffusion profiles in silicon devices.

Processes that utilize gases are typically highly energetic, requiring either high temperatures or high radiation levels. Therefore, particles in gases are able to bombard wafer surfaces with sufficient energy to drive mobile impurities from the surface into the film or crystal, creating material and electrical anomalies.

For the final filtration of gases, the best type of filter is a membrane filter, which exhibits the characteristic of being able to retain particles that are actually smaller than the rated pore size of the filter.

Photoresists

The photoresist solution is a particularly difficult fluid to filter, but this must be done to exacting standards, in order to ensure transfer of patterns onto thin films. Not only must the photoresist be filtered, but so also must the solvents used in developing the resist.

Particulate contaminants in photoresist are either undissolved polymers or manufacturing debris from the process of making the photoresist chemicals. Negative photoresist is formulated from high molecular weight products that are often difficult to dissolve and remove from the surface of the wafers. Positive photoresist, by its nature, is unstable with highly photoreactive groups. These can form reaction by-products along with auto-polymerized gels. The gel slugs are a source of pin holing image distortion, and oxide-island formation during the etch process.

Point-of-use filtration for photoresists is essential, and should be done at the last possible point, because in addition to impurities that may be present or formed during the photolithographic process, dispensing of the photoresist can also introduce particulate contaminants. Automatic dispensing machines can generate particles from pumps, valves, nozzles, tubing and residual photoresist deposited on these parts. Membrane filters are recommended for this application also, because they are highly efficient at removing substantial amounts of the gelatinous deformable polymers, along with the hard particles that are contained in the photoresist. As with chemicals the recommended pore size is 0.2 μm.

A prefilter should be used ahead of the membrane filter in order to reduce the pressure drop when filtering through the membrane, thus reducing the size of the housing needed for the filter cartridges. This will increase the life of the process system and take the load off the membrane filter that performs the removal of the finer particulates. As for the chemicals used to develop photoresists, continuous recirculation and membrane filtration are the preferred techniques. Strict temperature and atmospheric control must be maintained. Compressed air and water are two separate, but essential, tools in the production of electronic components and systems.

Food and beverage processing

The first reference to the use of filters for clarifying water, milk and wine can be found in Egyptian times. From wool and cloth, paper and charcoal to sea sand and sacking, many materials were used and found to be inadequate. It was not until the latter part of the nineteenth century, in Germany, that a satisfactory filter material was found to filter wine. That material was in fact asbestos.

In 1916 the sterile filter sheet became available for sterilizing filtration for the beverage and dairy industries. Other applications were soon found for this material, including vaccines, cosmetics, sugar, ink, film and paint processing. Today, however, asbestos is no longer used in the manufacture of filter sheets because of its toxicity. Considerable research has resulted in the availability of asbestos-free filter sheets that utilize cellulose fibres and mixtures of natural (uncalcined) kieselguhr and perlite. Other types of sheet also incorporate an advanced resin system.

Milk, beer, wine, soft drinks, potable water, syrups, edible oils, etc. must be filtered with products made from components complying with international food and drug regulations for food contact use. Extraction of binders or chemical additives from the filter and the migration of media fragments into the food are highly undesirable. Many pleated glass or resin-bonded fibre filter cartridge elements do not meet the food and drug standards (e.g. FDA regulations) because they can introduce glass fibres or resins into the product. Generally a binder-free, thermally bonded filter cartridge is preferred.

However, membrane filters are now standard for clarification duties in the brewery industry and are reasonably widespread throughout the whole of the food and beverage business as is shown in Table 4.4.

Depth filter cartridges can provide advantages in capital and operating costs over conventional sheet filtration using a plate and frame filter press. Polishing filters now produce beers with high clarity and low turbidity. Membrane filters also provide for microbiologically stable beer without the need for pasteurization. Aseptic packaging by means of filtration avoids the cost and negative flavour impact of pasteurization. Cold sterile filtered draught and bottled beers are very much in vogue and are an integral part of the entire production process.

Membrane filters have many advantages over thermal treatment (pasteurization), and should be technically capable of meeting the following specifications:

- retention of micro-organisms harmful to beer at low products temperatures
- no negative effect on essential beer specific components
- no ion release
- regeneratable with hot water
- effective regeneration with chemical agents
- no hydrolysis
- good wettability
- low product losses
- simple handling
- manual or fully automatic concepts
- low liquor and energy consumption figures
- cost-effective filtration because of high service life, and
- integrity testable.

Among the newer developments in membrane filtration in the brewing industry, ceramic cross-flow filtration membranes are gaining ground due to the fact that

Table 4.4 Membrane applications in the food industry

Dairy	RO:	(pre)concentration of milk and whey prior to evaporation
		bulk transport
		specialty fluid milk products (2-3X/UHT)
	NF:	partial demineralization and concentration of whey
	UF:	fractionation of milk for cheese manufacture
		fractionation of whey for whey protein concentrates
		specialty fluid milk products
	MF:	clarification of cheese whey
		defatting and reducing microbial load of milk
	ED:	demineralization of milk and whey
Fruits and vegetables	juices:	apple (UF, RO), apricot, citrus (MF/UF, RO, ED), cranberry, grape (UF, RO), kiwi, peach (UF, RO)
	pigments:	anthocyanins
	wastewater:	apple, potato (UF, RO)
Animal products	gelatin:	concentration and de-ashing (UF)
	eggs:	concentration and reduction of glucose (UF, RO)
	animal by-products:	blood, wastewater treatment (UF)
Beverages	MF/UF:	wine, beer, vinegar – classification
	RO:	low-alcohol beer
Sugar refining	beet/cane solutions, maple syrup, candy wastewaters	clarification (MF/UF), desalting (ED), preconcentration (RO)

(*Continued*)

Table 4.4 (Continued)

Grain products	soybean processing:	protein concentrates and isolates (UF)
		protein hydrolyzates
		oil degumming and refining (UF, NF)
		recovery of soy whey proteins (UF, RO)
		wastewater treatment
	corn refining:	steepwater concentration (RO)
		light-middlings treatment: water recycle (RO)
		saccharification of liquefied starch
		purification of dextrose (MF/UF)
		fermentation of glucose to ethanol
		downstream processing (MF, UF, NF, RO, ED, PV)
		wastewater treatment
Biotechnology	production of high quality water (MF, UF, RO, ED)	
	downstream processing (MF, UF, RO, ED)	
	cell harvesting, protein fractionation, desalting, concentration	
	bioreactors:	enzyme hydrolysis
		tissue culture
		plant cells

the pore size of the membrane can be controlled by the manufacturer and adjusted to the specific needs of the end-user. The pore size of a cross-flow microfiltration membrane has a considerable impact on the nature of the gel layer, or fouling, of the membrane, which in turn affects both beer flux and quality. It should be noted that definitions of pore size may well differ among membrane suppliers.

The filtration of bottle and keg washing water are applications that are frequently overlooked. Proper filtration of wash water is especially important when the bottle or keg will not be pasteurized. Micro-organisms from poorly filtered water can recontaminate non-pasteurized beer. Wash water should be filtered as carefully as the beer itself. Filtering sanitized water is also important, and should be carried out to at least the same level as for the process filters it will be sanitizing.

Infection of the wort damages beer quality, and a major source of contamination is improperly filtered aeration of the wort. Aeration requires a clean, well-filtered sterile air source for successful beer production. Hydrophobic (non-wettable) membrane filter cartridges are ideal for sterile air and gas filtration.

Dairy products

Reverse osmosis is used to considerable advantage in the food and dairy industry, the main reason being the cost reduction compared with evaporation consequent upon the elimination of this process. Some advantages and disadvantages of reverse osmosis in food processing are given in Table 4.5.

Table 4.5 Advantages and disadvantages of RO in food processing

Advantages	Disadvantages
Lower energy requirement	Expense and time to document product safety, and obtain approval of new membranes
Product quality separation without heat damage	Uncertainty of membrane durability and operating life, hence replacement cost
Reduced fresh water requirements	Questionable chemical inertness and pH sensitivity
Reduced waste treatment volume and cost	Limited operating pressure range in some applications
Potential increased profit margins from new products	Fouling with certain feedstocks
Relatively low floor space and capital requirements	

Applications of reverse osmosis in the dairy industry include water treatment, fractionation, product and chemical recovery, concentration and denaturing. The concentration of process streams from around 10% total solids to 25% can be achieved at a lower cost than by evaporation. Also there is a considerable reduction in volatile flavour component losses and in adverse changes to heat sensitive components (protein denaturation). Reverse osmosis also reduces discharge volumes to water treatment facilities and produces reusable water.

The performance of reverse osmosis in concentrating milk is limited by the osmotic pressure and most commercial modules have operating pressure limits of 30 to 40 bars, which limits the concentration of milk to a factor of three to four. In the production of skimmed or whole milk powder, the milk is usually concentrated to 45 to 50% total solids before spray drying. Thus reverse osmosis cannot substitute entirely for conventional evaporation, rather it is used as a pre-concentration step before evaporation, to reduce operating costs or to increase capacity of existing plant. The relative energy consumption of reverse osmosis and thermal concentration methods in the concentration of milk differ by an order of magnitude, and with thin film composite membranes the cost of reverse osmosis is lower still.

The ultrafiltration of milk using polysulphone or polyethersulphone type membranes has a number of applications. The ultrafiltration of milk on farms as a means of reducing refrigeration and transport costs, and the production of speciality milk-based beverages are attractive uses. Cheese manufacture using ultrafiltration is another area where the use of membrane filtration is becoming more widespread in the dairy industry.

The fractionation of whey by ultrafiltration to produce protein concentrates can increase the initial protein content from 10 or 12% (dry basis) to 35, 50 or even 80% protein with little loss in whey protein functionality. Demineralization of whey can be achieved by ion exchange, electrodialysis and nanofiltration.

Food and beverages

Soybean is an important source of protein, and the process to recover the protein and fat requires the removal of undesirable compounds. Traditional removal methods include extraction, heat treatment and centrifugation to separate the protein and fat from these compounds. Hollow fibre ultrafiltration modules are used to recover full fat soy protein concentrates and soy isolates.

Animal product processing utilizes ultrafiltration to remove biologically degradable matter from wastewaters to give a permeate suitable for discharge to a sewage system.

Fruit juice processing is a major use for membrane filters, particularly for clarification (using microfiltration or ultrafiltration), concentration (using reverse osmosis) and deacidification (using electrodialysis). The clarification of apple juice by ultrafiltration is now an important process, whether making clear juice or ‘natural’ (i.e. cloudy) ones.

Developments continue on citrus fruit processing. The membrane configurations most often used in juice clarification are tubular membranes or hollow fibre modules, as well as plate and frame systems using flat sheet membranes. The traditional method of concentrating juices and purees has been evaporation, but nowadays reverse osmosis is proving successful. Reverse osmosis plant performance depends on juice viscosity, the osmotic pressure of the solution, and the constraints imposed by the need for a particular product quality.

Potential applications of membrane processes in cereal production are in the treatment of stillage, in corn wet milling operations, evaporation of steep water, concentration of dilute sweet waters, and in polishing of reverse osmosis permeate and evaporator overheads. Corn proteins can be recovered from stillage solubles of dry milled fractions of corn, grits, flour, degerminated meal, etc. by reverse osmosis.

Ultrafiltration is also used to fractionate and concentrate proteins from potato processing wastewaters. Other protein wheys can be processed by reverse osmosis. Electrodialysis is used for a number of applications in the food and beverage industry, including deionization or deacidification of fruit juices, wines and, in the dairy industry, milk and whey. It often competes directly with ion exchange processes.

Whilst membrane filtration has made great progress in the food and beverage industries, the more traditional sheet filter still holds an important part of the business. Typical filter sheets used in beverage processes are designed to be of a standard thickness, and to use only natural kieselguhr and perlites. Other sheets use natural kieselguhr as the filtration active ingredient combined with processed wood pulps as extenders. Pure cellulose sheets incorporating wet strength resins within the matrix of the sheet are used in plate and frame filter systems (Figure 4.27). Filter aids may be applied initially as a precoat layer and subsequently as an addition to the main feedstock. Other filter sheets include the addition of activated carbon.

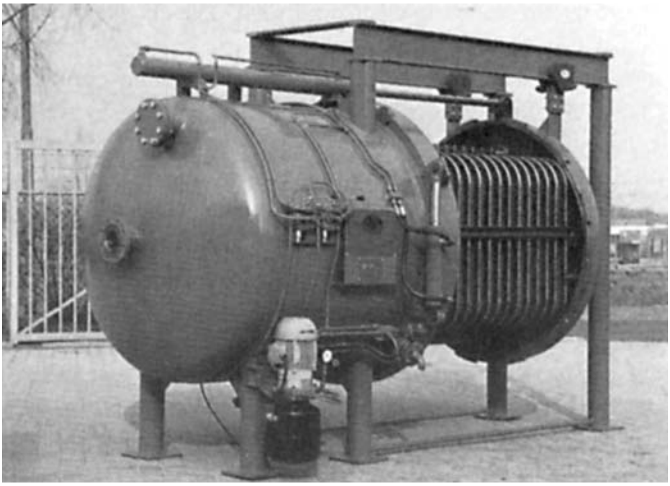


Figure 4.27 Plate and frame sheet press

In wine production, chemical and biological stability are vital. To achieve chemical stability, it is essential to eliminate from the wine excess amounts of heavy metals such as iron and copper, of tartrates and sometimes of albumens. For biological stability, it is necessary to ensure the wine is free from yeast and bacteria. Filtration plays a major part in these separation processes. Sheet filters, consisting of a flush plate filter or a plate and frame filter press, are used as standard equipment in the wine industry. Standard sizes use 40 × 40 cm or 60 × 60 cm elements.

The metal surfaces of the filter plates and the expanded metal inserts and filter frames, in contact with the wine during processing, are preferably made from 316 stainless steel with smooth polished surfaces to prevent microbiological contamination. The first stage at which wine is filtered is likely to be at the time of first racking.

Generally, kieselguhr is used as the filter medium. For this purpose, the plate and frame filter is usually dressed with a high wet strength cellulose sheet suspended over, and supported by, the outlet collection plate. The precoat and filter beds are deposited on the cellulose sheet and the bed is built up in the inlet frames or chambers on either side of the outlet plate. The filter is cleaned at the end of a cycle and sheets can generally be used again.

The quantitative performance of the filter is dependent on the hourly flow (which in turn is dependent on the filtering surface area) and on the total throughput per cycle (which is dependent on the available cake volume).

In the brewing industry, the filtration of fermented beer, following a period of cold storage, is still widely practised as a two-stage operation with final sheet filtration. The first removes visible turbid matter and uses kieselguhr as the filter medium in a filter press. For sheet filtration as a final stage, it is important to use stabilizing sheets to give the beer greater stability against chill and oxidation hazes by removing a proportion of anthocyanogens and to shorten the cold storage time.

The filtration of whiskies prior to bottling, of either blended or straight malt types, is essential to ensure shelf-life, stability and clarity. The process is by no means straight-forward, and it is of importance that the correct equipment and filtration media are utilized, and that the filtration is conducted under carefully controlled conditions. Filter presses are generally used to remove chemical and physical hazes, including ethereal oils. It is common practice for whiskies to be chilled prior to final filtration to assist the build-up of large globules of oils on the filter sheet surfaces. The presence of air in whisky must be excluded during filtration.

In the soft drinks factory, the main ingredients to be filtered are the sugar syrup and water for the bottling process. Filtration of sugar syrup is a batch process, in which measured quantities of sugar and water are mixed together, filtered under pump pressure and transferred to a vat. Filter presses are used extensively for sugar syrup filtration. Filtration rates for sugar syrup solution will vary according to viscosity, quality of sugar, etc. from as high as $950\,\mathrm{l/m^2\,h}$ to as low as $300\,\mathrm{l/m^2\,h}$.

Outside the food and beverage industries, there are many other applications for sheet filtration. Some of the more important include antibiotics, medicinal syrups, toilet and cosmetic preparations, gelatine and vinegar.

Gelatine liquor usually involves a multi-stage filtration process. Primary filtration removes coarse particles of suspended matter, and secondary filtration further improves the clarity and imparts a brilliance to the liquor. Where the gelatine liquors are to be passed through ion exchange columns, coarse filtration takes place before the deionization stage. The primary operation is best accomplished with kieselguhr as the filter medium. Washable type support sheets are used. Secondary filtration should occur at a stage in the concentration process where the combination of throughput and viscosity is considered ideal for optimizing the filter specification.

Vinegar is normally filtered at the bottling stage. Sterilizing filter sheets are required for malt and wine vinegars.

Bioprocessing

Bioprocessing refers to the production of biologically active therapeutic and diagnostic proteins that are expressed by mammalian or bacterial cells. A series of unit operations isolates and purifies the products of fermentation. A schematic drawing showing the various unit operations involved in a typical bioprocessing activity is given in Figure 4.28.

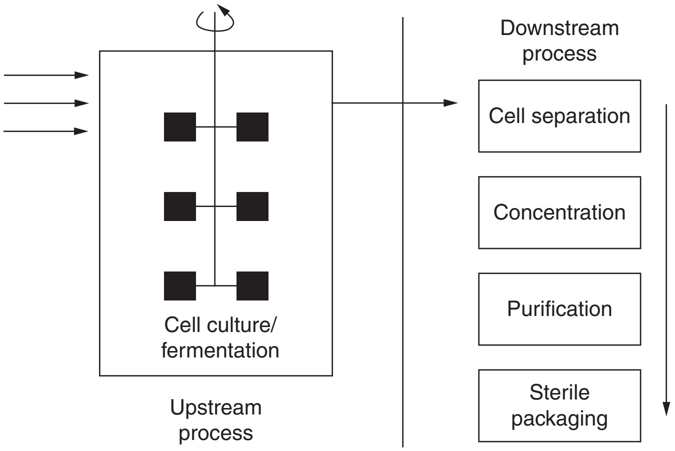


Figure 4.28 Bioprocessing operations

In most cell culture and fermentation processes, air and liquid nutrient feed streams are clarified and sterile filtered to eliminate particulate and microbiological contamination of the fermenter. Serum and culture media feeds are sterile filtered with membrane cartridges to remove contaminating micro-organisms. Hydrophobic filters provide sterile filtration of inlet fermentation air.

Cell separation in the downstream processing stage recovers the product from the fermentation broth. Initial clarification steps separate the biomass from the desired product in solution. Depth filtration can provide effective, economical cell separation for removing cells, cell debris, endotoxin and contaminating host cell DNA. Cartridge systems can offer advantages over competitive technologies such as plate and frame filter presses.

Concentration and purification in downstream processing is dependent on the nature of the product to be recovered. Chromatographic columns should be protected with prefilters, and chromatography buffers should be membrane filtered. Sterilizing grade membrane filters provide sterility of the final parenteral product just prior to filling operations. Prefilters provide high contaminant-holding capacity while protecting downstream filters. Hydrophobic tank vent cartridges maintain a sterile environment in product holding tanks.

Chemicals and solvents used in biological manufacturing include alcohol, acetone, methylene chloride and numerous other aggressive materials. Filters required for chemical and solvent filtration include coarse prefilters, fine prefilters, membrane prefilters, final sterile filters and tank vent filters.

Air and gas systems requiring filtration include sterile filtration of inlet fermenter air, pressure sources for tank to tank transfers and cooling media for holding tanks after sterilization. For sterile manufacturing processes, gases coming into contact with the product are always sterile filtered. Typically, 0.2 μm filters provide reliable sterile filtration of air and gas in bioprocess manufacturing environments. Biological treatment of wastewater streams range from municipal and industrial to landfill run-off wastewater filtration. Biological treatment reduces and decomposes water pollutants into nitrogen, carbon dioxide and water. Disc and decanter centrifuges and sludge separators are normally used to separate biomass from the reactor outlet stream. Tubular and multi-tubular membranes can also offer advantages in complete biomass rejection.

The effective removal of grease and fats, and the frequent occurrence of a poor settling biological sludge, have often been problems for the dairy industry. A process for dealing with the latter problem when treating wastewater by the activated sludge process has been developed. It is still an activated sludge process, but differs from the conventional system by employing dissolved air flotation as the liquid-solid separation system for both primary and secondary stages.

Fine chemicals

Filtration is normally called for prior to filling toiletry and cosmetic containers. Sheet filters are normally employed for this purpose. In this sector are commonly found applications for medium or fine clarification, involving eau-de-Cologne lotions, after-shave preparations, toilet waters, etc. (some of which are spirit based and some water based). Ultrafiltration is used, in the manufacture of natural cosmetic products, for the clarification of concentrates for fruit and salad based products that are included in cleansers, moisturizers, bath products and face creams.

Advances in chemical and pharmaceutical technology allow for processing of products in one sealed unit where previously transfer between different pieces of equipment was required. The general processing steps available in such a unit are as follows:

1. filtration of slurry, aided by pressurizing the vessel and/or applying a vacuum on the underside of the filter medium
2. washing of the cake using a spraying system
3. resuspended filtering and washing the cake

4. smoothing and drying the cake using hot gas purging and the application of a heating jacket and jacketed filter plate
5. drying the cake under vacuum with the agitator raking up the cake, and
6. the ability to remove the cake through a solids discharge door in the vessel side or at its top.

Such vacuum filter dryers are used for processing pharmaceuticals, fine chemicals and toxic products, and can use a variety of filter media including sintered metal plates, woven wire mesh and a wide range of fabric cloths. Most processing steps can be carried out either under vacuum, or an inert gas such as nitrogen, or under normal atmospheric conditions. Dissolved solids can then be crystallized by application of cooling in the jacket.

During the filter/wash cycle the unit is held with the filter plate lowermost. Vacuum is maintained below the plate and mother liquor drawn off to a separate receiver. A smoothing agitator is used to level the cake and prevent cracking in it so as to maintain the vacuum. When the initial filtration is completed, the cake can be washed by introduction of fresh water or solvent. The filter cake is dried by rotating the unit about half a turn to bring the reactor section lowermost and slightly inclined from the vertical. On completion of drying the product is discharged through the loading port, or by some other means. The filter dryer can actually be quite a large piece of plant as is shown in Figure 4.29.

Figure 4.29 Filter dryer

Disc stack, decanter and tubular bowl centrifuges are used for a wide range of separation duties in the pharmaceutical and fermentation industries, including liquid-solid, liquid-liquid, liquid-liquid-solid separations, and liquid-solid extraction. Typical process steps include cell harvesting, concentration and washing, cell debris removal, inclusion body recovery and purification, solvent extraction, dewatering and recovery.

Disc centrifuges differ in the amount of solids they can handle for a given feed and in the way the solids are removed from the separating vessel. Solids-ejecting types are more suitable when the solids concentration in the feed fluctuates. They remove the solids intermittently while the machine is at full speed, or continuously through nozzles at the periphery of the bowl. Solids retaining centrifuges are generally intended for separating liquids that contain only a small amount of solids; the solids accumulate inside the bowl of the separator, which needs to be stopped at intervals for the accumulated solids to be manually removed.

Decanter centrifuges, for process applications, are typically solid bowl scroll-discharge machines, capable of continuous solid and centrate discharge. They are ideally suited to handling high feed solids concentrations and delivering dry solid products. They are generally able to convey the soft solids often encountered in the pharmaceutical and fermentation industries.

Tubular bowl centrifuges usually incorporate continuous centrate discharge and batch solids recovery, and operate at variable speeds up to 20,000 G. Although primarily intended for liquid-liquid separation, they can also be used for recovery or classification of ultra-fine solids. These sedimenting centrifuges (disc, decanter and tubular bowl) are described further in Section 7.

Centrifugal filters are also used quite widely in the fine chemicals and pharmaceuticals sector. They can either be of the perforated basket type (as shown in Figure 4.30), with manual, bag or knife unloading of filter cake, or the peeler, operating with a horizontal axis and with cake removal by a peeling knife into a discharge chute.

Figure 4.30 Centrifugal basket filter

Paints and inks

Process filtration in the manufacture of paints and inks includes the treatment of adhesives, resins, and process and wastewater, as well as paints, varnishes, inks and other coatings. Bag filters (Figure 4.31) and bonded media filters are often used for high-viscosity applications such as the removal of oversize particles from paints and inks.

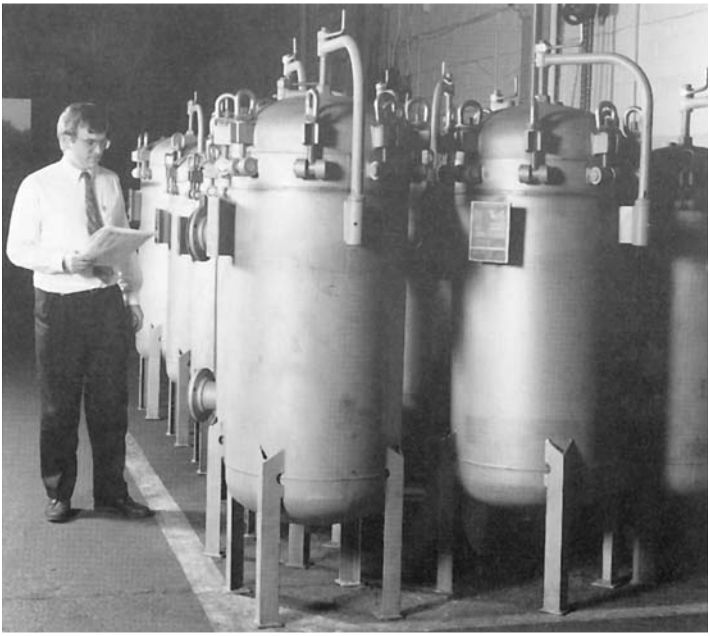


Figure 4.31 Bag filters for paint filtration

Cathodic electrocoating is employed extensively in the automotive industry, where basically three filtration systems are commonly used:

- ultrafiltration for separating suspended solids, colloids and high molecular weight materials in solution
- strainers for separating large diameter suspended solids, and
- bag filters made from meltblown polypropylene for separating suspended solids between 1 and 800 µm.

Rigid depth filter cartridges retain deformable or soft agglomerates of oils, gels, fluoro-carbons and silicones. These are among the most difficult contaminants to remove from a coatings application. The deformables are retained by coalescence, surface tension and adsorption. Other contaminants such as large, rigid particles or small agglomerates of particles can be removed by absolute-rated filters with good classification characteristics.

Non-rigid filters such as bags and meltblown cartridges compress and relax with pulsating pumps, or pumps that are cycled on and off. These pulsations can affect the pore size of the medium and alter removal efficiencies. Non-rigid filters, such as yarn-wound and some meltblown cartridges, may exhibit unloading of contaminants once a critical differential pressure is reached. Rigid filters typically maintain the desired filter pore size regardless of the differential pressure. Surface filters such as bags and vibrating screens are more likely to release fibres and deformables than are depth filters.

Bag filtration used in electrocoating of metal parts has proved successful for a number of reasons. These include:

- low investment cost
- low replacement cost
- high dirt-holding capacity
- ability to filter at high volumetric flow rates, and
- up to 99% filtration at a given micrometre rating.

Spiral-wound membrane modules, with hydrophilic membranes, are suited for water-based paint recovery in spray paint installations, and also for electrocoat paint filtration. Figure 4.32 shows a schematic for an ultrafiltration system for treating spray booth waste.

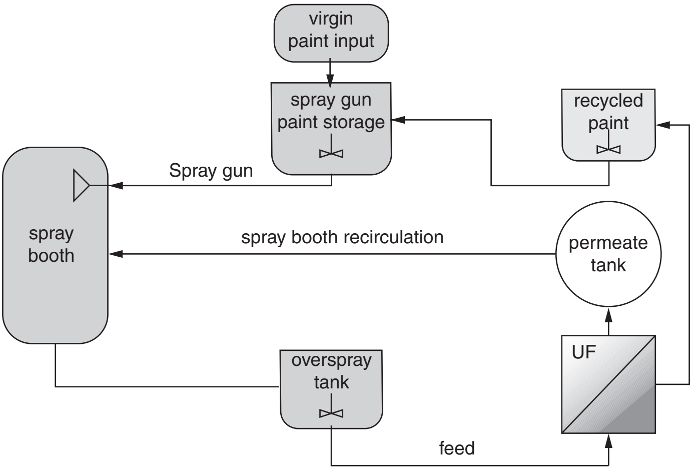


Figure 4.32 Water-based paint recovery

Ceramic microfiltration is another technology that is being applied in solvent and water-based paint production, and paint applying, industries for the treatment of paint-water mixtures, plus other areas such as oil-water emulsions, compressor condensate and degreasing baths.

Pulp and paper

Massive quantities of water are consumed in the pulp and paper industry. Water is used as the suspending liquid for the pulping process and the bleaching stages as well as for washing. As a result, large volumes of effluent water are produced that need to be filtered.

Ultrafiltration processes have proved successful for the treatment of effluents, the treatment of black liquor, bleaching effluents and paper machine wash waters. They have also found use in the treatment of Kraft process effluents and there is increasing use of ultrafiltration to recover lignosulphonate and alkali lignin from the spent liquors to produce other products. Reverse osmosis is used in the pulp and paper industry for concentration of sulphate liquor, using plate and frame modules and cellulose acetate membranes. Reverse osmosis is also used in the treatment of bleach effluents after various pretreatment stages.

Textiles

Several applications for ultrafiltration and reverse osmosis are being employed in the textile industry. These include the treatment of size and latex contaminated effluents, wool wash waters and effluents from dying operations. The membrane processes are alternatives to the classical mechanical, biological, and physical-chemical processes, such as precipitation, flocculation, flotation and adsorption. An increasing use of membranes is evident in the ultrafiltration of sizing agents used to coat yarns during weaving, where the filtration process is used for water soluble and low-viscosity size. Higher recoveries can be achieved but at higher investment cost.

Membrane processes can also be used in the treatment of bulk dyehouse effluents, wool and yarn scouring effluents, process water, and effluents containing mothproofers and other pesticides. Reverse osmosis, for example, can be used to recover up to 80% of warm dyehouse wastewater for re-use. A membrane life span of two years is typical. Ultrafiltration using polysulphone membranes may be very effective in the wool scouring process, for concentrating the more significant pollutants into a small volume. It can also produce large quantities of permeate suitable for re-use in the scouring process.

4G. SURFACE TREATMENT CHEMICALS

Manufactured metal parts and finished products may go through a whole series of surface treatment processes. These include chemical and electrochemical operations such as washing, pickling, degreasing, phosphating, galvanizing, plating, etc. as well as numerous rinsing stages. Considerable economies can result from effective filtration and clarification of the various fluids involved, and, in the case of highly automated systems, such treatment becomes essential in order that the fluids used should continue to be dependable. Further, many operations may produce sludges, often containing toxic metal salts presenting a difficult disposal problem. Here there can be considerable advantages in employing sludge dewatering to compact a large mass of wet, sticky substance into a much smaller and more easily handled dry cake, which may or may not have further value. The dewatering process may, at the same time, recover valuable process fluid.

Clean water is an essential requirement for anodizing, plating and similar processes, which may require softening or carbon purification of the raw water supply. Certain processes also require the use of deionized water, which can be obtained with ion exchange or reverse osmosis treatment. In all such cases, prefiltering of the water is highly desirable to eliminate solid contaminants that could reduce the efficiency of the water treatment process involved. A suitable filter rating here is 15 μm. The treated water can then benefit by post-filtration to capture any migration of the treatment medium, such as could occur with powdered activated carbon purification.

Where there is no stringent demand on water quality for processing, a filtered water supply is still desirable to prevent clogging of nozzles, sprays, control valves, etc. and to reduce wear on pumps. It also becomes essential on recirculating systems, especially where the water is used for washing. The choice of filter in such cases is usually dependent on the amount of solids likely to be present, the degree of protection desirable (i.e. the required filter rating), available space and cost.

Degreasing baths

Aqueous degreasing processes use alkaline or acid solutions containing chemicals and various additives. These baths become contaminated with oil and when the bath loses its efficiency, its contents have to be renewed, at a high cost, or the oil must be removed. A well tested method for oil removal is based on using CFCC (carbon fibre-carbon composite) filter membranes, and permanently hydrophilic polymer membranes.

This process (Figure 4.33) can remove oil from either immersion or spray type baths. In operation, part of the bath volume is continuously drawn off and treated to remove an amount of oil equal to the process input. Pretreatment first removes the free oil and solids. It then passes to a concentration tank where the oil is continuously

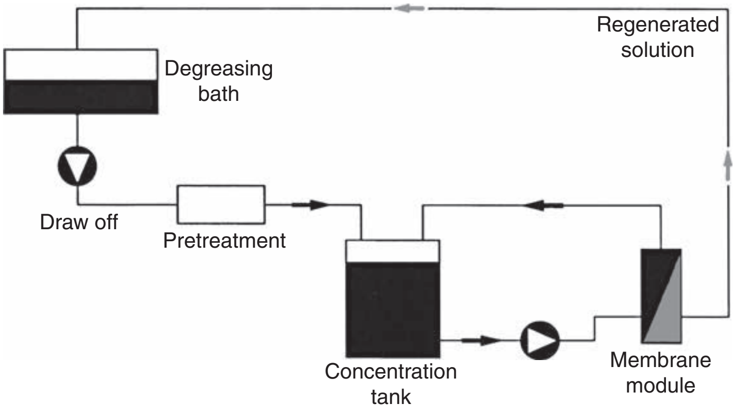


Figure 4.33 Degreasing flow schematic

removed by circulation over CFCC membranes. The oil-free solution is then returned to the bath. When enough oil has collected, the concentration tank is emptied.

The process is purely a mechanical separation. Batch bath regeneration is also possible.

A simple device, shown in Figure 4.34, is employed for point-of-use cleaning of degreasing solutions. This is designed to operate without prefiltration and with low maintenance. It incorporates stacked filter housings and a rotating disc with spiral grooves to eject fluid across the filter surface in a vortex flow pattern, which sweeps the solids off the filter surface, preventing permanent fouling of the filter pores. The equipment is housed in a standard drum. Periodically, concentrated oils can be skimmed or pumped from the drum or the entire drum may be removed for disposal.

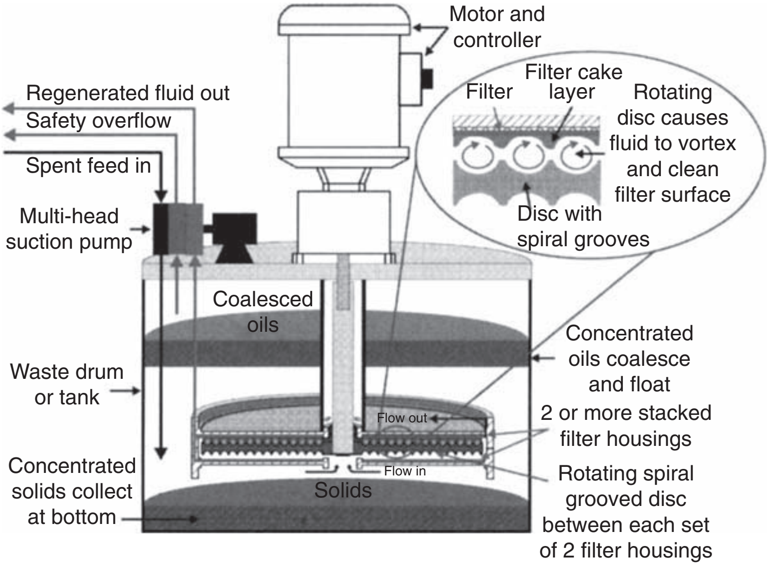


Figure 4.34 Simple solution recycling unit

Electrodialysis

A number of surface treating processes require a rinsing fluid, which dissolves salts produced in the process. It is possible to recover more than 80% of the salts in a rinsing fluid using electrodialysis equipment. This electrochemical process is particularly suitable for recovering salts of silver, copper, nickel and zinc. The method involves a large number of electrolytic cells in series. Each cell comprises a cationic membrane and an anionic membrane, with a spacer between each pair of membranes.

Positive ions (cations) pass through the cationic membranes towards the cathode, but they cannot pass through the anionic membranes. Similarly, negatively charged ions move in the opposite direction, towards the anode, passing through the anionic membranes but then being stopped by the cationic membranes. The result is that in one cell the solution is enriched both with positive and negative ions (i.e. with the whole salt), whilst in the adjacent cells the concentration of both positive and negative ions is reduced (i.e. the solution is deionized).

Applications for electrodialysis include:

- mother liquor demineralization from crystallization
- recovery and concentration of acids
- treatment of fermentation liquors
- ionic standardization control of ionic concentration, and
- substitution and double decomposition reaction.

Acid cleaning and pickling baths

It is normal, in non-automated acid cleaning and pickling baths, for there to be no filtration of the solutions, the solid contaminants being allowed to settle out of suspension. Batch filtration can, however, substantially improve acids life and simplify waste treatment. A typical array of equipment used for pickling solution recycling is shown in Figure 4.35, similar to most of the solution treatment processes described in this Section.

Figure 4.35 Pickling solution recycling plant

Alkaline cleaning solutions

Alkaline soak-cleaning solutions and electro-cleaners generally accumulate considerable amounts of solids and organic contaminants, as well as floating scum. This last is normally removed by skimming. Solids can be removed by settlement when the plant is idle, followed by decanting (drawing off of) the fluid, and removal of the settled solids. Fluid itself is replaced periodically, as necessary, such as when sample analysis shows that it is reaching the end of its usable life. Where heavy dust loads are involved, continuous or periodic (batch) filtration, with a relatively coarse (50 µm) filter can show considerable economic advantages.

Anodizing solutions

Anodizing solutions are not generally filtered on non-automated plants, although periodic batch filtration is desirable. Seal solutions benefit from continuous or bypass filtration, and may also require periodic carbon treatment to remove discolouration from the dyes used. A filtration system comprising a main filter element and an activated carbon chamber can provide continuous protection throughout the life of the element and carbon content. Ideally, a separate filter should be used on the seal tank.

Phosphating solutions

Phosphating solutions contain either zinc, iron or manganese phosphate and phosphoric acid with suitable accelerators. During the process, the clean steel parts are immersed in (or sprayed with) the metal phosphate-phosphoric acid bath, iron is dissolved at the surface and a phosphate coating is formed. The operation of these baths requires an even application of solution and good chemical control. Sludge accumulation results in poor quality, lost production and need for frequent maintenance. The sludge generated will not harm the phosphate process as such, but is detrimental to the operation since it tends to foul and plug heat exchangers, circulating pumps and strainers, spray nozzles, etc. The sludge must therefore be removed, preferably with an automatic separation system, such as the continuous roll filter shown in Figure 4.36.

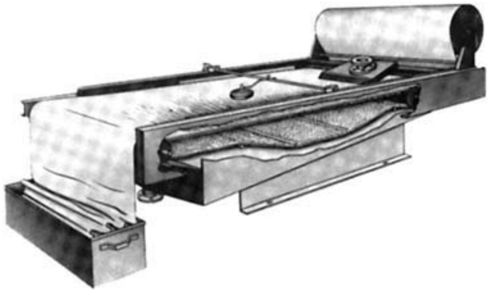


Figure 4.36 Flat bed (roll) filter for phosphating solutions

Zinc phosphate baths require acid resistant materials, such as 316 stainless steel. They generate more sludge than the iron phosphate baths, which can be handled with carbon steel and cast iron. The filtration of two or more tank turnovers per day using a filter medium with moderate porosity (25–40 µm) has proved effective. A tapered bottom phosphate tank aids in conveying the sludge to the pump. Either in-tank or out-of-tank pumps may be used to transfer the sludge-laden solutions to the filter. Filtrate is returned to the phosphating tank by gravity or a sump pump in the clean reservoir of the filter.

The continuous belt filter, shown in Figure 4.37, is a type that is particularly well-suited for the continuous cleaning of phosphate bath solutions. The framework of the filter is constructed in unstressed steel, the outer faces being tied together by diagonal struts. The collecting sump has an outer flange connection (8) for the removal of the filtrate; there is a slurry scraper (9) and waste chute (10) for the slurry. The band filter bed is a perforated plastic sheet (4), with a continuously circulated filter band (3) above it in plastic material. The solution inlet (2) has an adjustable deflector plate and an inlet connection (1) for the unfiltered phosphate solution. A spray installation for water (6) and compressed air (7) consists of two oscillating nozzle jets, and two magnetic control valves for controlling the operation. Band transport is through a drive motor (5).

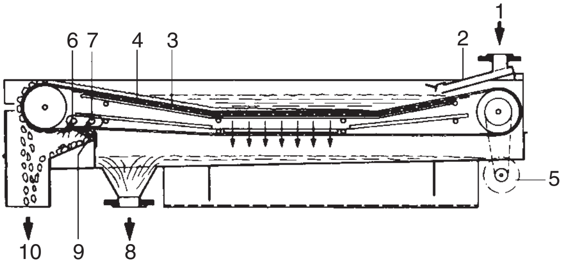


Figure 4.37 Belt filter for cleaning phosphate baths

In operation, the unfiltered solution flows through the inlet (1), to the inlet chamber (2), through the plastic filter band (3), into the collecting sump and through the outlet (8) back to the bath. The impurities build up on the bed of the filter band (3) into a sludge layer. The layer thickness depends on the bonderizing process being used. The layer formation reduces the porosity and so raises the quality of filtration. As the filter band (3) moves forward, the filter sludge is dropped out through the waste chute (10). At the same time, the forward movement of the band opens two magnetic valves for water and compressed air; two nozzle jets (6 and 7) spray the returning conveyor band from the reverse side and clean off any slurry residue.

Plating solutions

Virtually all plating solutions benefit from continuous filtration. They also require periodic purification to restore their clarity, particularly those solutions containing wetting agents, since any oil introduced with the bath is dispersed throughout the solution and can be deposited on workpieces causing peeling or imperfect plating. Purification is commonly done with activated carbon treatment. The range of plating processes and the general treatment recommendations are summarized in Table 4.6.

Electroplaters often specify finer filter media than necessary. Solids are added to a solution continuously so it is impossible to maintain a working solution 100% free from solids contamination. Therefore, the plating process is always carried out in a

Table 4.6 Plating solution properties

Process	pH	Bath temp (°F)	Filtration	Filter rating (μm)	Carbon treatment
Anodizing	1	60–90	Optional	15	No
Anodizing Ni seal	5.5	200	Desirable	15	Batch
Brass, bronze	10	100–200	As required	15	No
Cadmium	12	100	As required	30	No
Chromium hexavalent	1	110–130	Optional	15	No
Chromium trivalent	2–3.5	75	Continuous	1–5	No
Copper acid	1	75–120	Continuous	15	Periodic
Copper cyanide	11–13	70–150	Continuous	15	As needed
Copper electroless	14	100–140	Continuous	3	No
Copper fluoborate	1	70–120	As required	15	As needed
Copper pyrophosphate	8–9	110–130	Continuous	10–20	As needed
Gold acid	3–5	80–125	Continuous	1–5	Periodic
Gold cyanide	7–12	75	Continuous	5	Periodic
Iron chloride	1	195	Continuous	15	Yes
Lead fluoborate	1	100	Continuous	15	No
Nickel bright	3–5	125–150	Continuous	15–30	Yes
Nickel semi-bright	2–5	130	Continuous	15	Yes
Nickel chloride	2	120–150	Continuous	15	Yes
Nickel electroless	4–11	100–200	Continuous	15	As needed
Nickel sulphamate	3–5	100–140	Continuous	15	Yes
Nickel watts	4	120–160	Continuous	15	As needed
Nickel-iron	3.5–4	135	Continuous	15–30	Yes
Rhodium acid	1	100–120	As required	5	Periodic
Silver cyanide	12	70–120	Continuous	5	Periodic
Tin acid	0.5	70	As needed	15	As needed
Tin alkaline	12	140–180	As needed	30	No
Tin lead (solder)	0.5	100	Continuous	15	Periodic
Tin-nickel	2.5	150	Continuous	15	Yes
Zinc acid chloride	3–5	70–140	Continuous	15	No
Zinc alkaline	14	75–100	As needed	30–50	Optional
Zinc cyanide	14	75–90	Continuous	30–100	No

solution that is to some degree dirty. It is of little value returning crystal clear solution from the filter to the plating vat if the rate at which contaminants are added exceeds the rate at which they are removed. The filtration rate of flow is all important. Tests have shown that when one tank volume was filtered per hour, 63% of the dirt load was removed. When the flow rate was increased to two tank volumes per hour, 86% of the dirt load was filtered from the solution, and when the rate of flow through the filter was raised to five tank volumes per hour, over 99% of the solids were removed in that hour. The golden rule on selection of micron rating is to choose the coarsest medium possible consistent with good roughness-free plating.

Chromium plating

The thickness of chromium deposits from an electroplating solution range from light to heavy, using bath temperatures from room temperature up to 60°C. Continuous filtration down to 15 μm is desirable to achieve the highest possible clarity and deposit quality. The more recently introduced trivalent chromium plating baths require continuous filtration with dense filter media to remove the fine particulate matter formed during plating. Since the bath does not tolerate any metallic contamination, contact with all metals, including lead, must be avoided.

With self-regulating baths, care should be taken to filter the solution off the top only and to bypass around the filter during agitation of the self-regulating chemicals. Any solids from the self-regulating bath that are picked up by the filter will be dissolved in time, as required. The purpose in keeping them from the filter in large quantities is to prevent the solids from restricting the flow through the filter and reducing the amount of agitation. With an oversize filter, the regulating chemicals can be retained on the surface of the filter medium without reducing flow too much.

Nickel plating

With nickel plating baths agitation is usually recommended, and organic compounds are added to get the best levelling and brightness. Other nickel solutions are used for engineering and salvage applications, or electroforming, which demand a near perfect plate. These contain anti-pitting agents instead of organic brighteners. Bright and semi-bright nickel electrolytes require the continuous or periodic removal of organic breakdown products from brighteners with activated carbon. Carbon purification may be desirable for nickel solutions prior to the addition of wetting agents. Initial and continuous carbon treatment with at least two tank turnovers per hour are suggested. The newer nickel-iron plating baths must be filtered and purified like any other bright nickel solution.

Electrolytic purification by ‘dummy’ plating to remove undesirable metallic impurities, such as copper, is frequently employed in conjunction with filtration equipment, by either pumping from a separate tank or weir filled with overflow solution, or by recirculating through the slurry tank for this purpose.

Solids can be removed from the bath by recirculating the solution through a filter that employs filter media with an average particle retention of 15 μm down to submicrometre levels, with or without filter aid. Flow rates per hour will also vary from two to ten times the volume of the tank. One tank turnover per hour is not sufficient in most cases to remove all the solids in suspension before they settle to the bottom. Sedimentation in the plating tank requires periodic cleaning, and therefore down time, of the tank. Coarser, or slightly denser, media may be used depending upon the dirt load, and the degree of clarity required. With a higher flow rate, a coarser filter medium will attain the same degree of clarity as a denser medium, at a lower flow rate. The coarser filter has a higher dirt-holding capacity and a longer life.

Zinc plating

Zinc plating in acid baths, using zinc sulphates, produces a matt zinc deposit and is primarily used for coating steel wire and strip. Zinc chloride baths produce a lighter deposit. Continuous filtration in the order of 10–15 µm is recommended in both cases. Acid zinc baths are susceptible to contamination with iron, which must be periodically precipitated as iron hydroxide by hydrogen peroxide treatment. This precipitate is difficult to filter because of its gelatinous nature.

The newer alkaline zinc plating baths deposit zinc faster, with better uniformity and yield a bright coating, provided solution quality is maintained. Coarse filters must be used, at 50 to 100 µm because of the slimy nature of the sludge formed, with periodic carbon treatment to remove organic impurities. Continuous filtration is recommended with solution agitation and strict bath temperature control; batch filtration is also used. In this case the sludge is allowed to settle before the solution is drawn off for filtration and is then cleaned from the tank before refilling. Precoat filters employing kieselguhr should not be used with alkaline zinc plating solutions, since any silicates present may dissolve in the solution.

Copper plating

High-throw acid copper sulfate plating baths require continuous filtration (at 15 µm) at high flow rates, to ensure uniform deposits, together with periodic carbon treatment to remove organic impurities. Systems consisting of pump and filter combinations are recommended with a separate carbon chamber for periodic purification when necessary. Slurry tanks, and related piping and valves, are useful if the baths have to be batch carbon treated, and when being made up before the brightener is added. The slurry tank provides for easier pump priming and addition of chemicals. A carbon canister purification chamber can be adapted to any filter with a bypass valve and piping to control the flow through the carbon. Plastics, such as polypropylene, PVC or CPVC, are the most suitable materials for pump and filter construction.

Dip plating solutions

Chemical solutions for direct copper and nickel plating are normally filtered after make-up and pH adjustment, and periodically batch filtered at suitable intervals. Carbon treatment may also be required periodically, to remove organic impurities, but for this the solution must be cooled to a non-active temperature. Non-metallic filter elements and filter construction must be employed, with a suitable filter rating being 15 µm. Baths operate at temperatures up to 95°C. The filtration of electroless nickel solution removes nickel phosphate, which is a by-product of the plating process. Since its solubility is lower in hot solutions than cold, hot filtration is more effective. If allowed to accumulate, it adversely affects bath stability and deposit appearance. Cloudiness or precipitation in a used bath is generally due to nickel phosphate. If continuous filtration is employed and the filter is located upstream of the heat exchanger used to heat the solution, flow through the heat exchanger will gradually decrease as the filter collects contaminants.

Purification by carbon treatment

Several mentions have been made of plating bath purification by means of activated carbon treatment. Activated carbon can be used to purify most plating solutions, but should be preceded by filtration (if the system is not continuously filtered) to prevent contaminant particles covering the carbon surface and reducing its effectiveness. There are four basic methods of carbon treatment:

1. carbon cartridge filters to fit standard filter housings and suitable for use on small volume systems
2. carbon canisters holding granulated activated carbon for bypass or batch filtration (Figure 4.38)

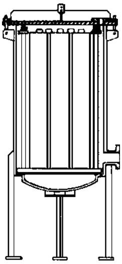


Figure 4.38 Housing for canisters of activated carbon

3. bulk carbon treatment when granular carbon is loaded into a filter chamber incorporating a separate filter element, and
4. carbon precoat filters using powdered carbon.

In cases 2 and 3, as a general guide, approximately 1 kg of carbon is needed to treat every 1000 litres of plating solution for batch filtration. Flow rates should be relatively slow, to allow sufficient contact time for effective adsorption. Faster flow rates are possible with carbon precoat filters because of the large surface area offered by powdered carbon.

4H. METAL WORKING FLUIDS

Most metal working operations call for the use of lubricants and coolants to lubricate the surface between the workpiece and the tool, and to remove heat generated by the process. Additional advantages offered by such fluids are the sluicing away of fine swarf from the work area, and corrosion inhibition. The most common choice for a metal working fluid is an oil-water emulsion, with the oil content providing the lubrication, and the water acting as the main cooling agent; such fluids are generally referred to as coolants.

The use of suitable filtration and clarification equipment is almost essential for machining applications including:

- internal and external grinding
- profile, thread and slot grinding
- high precision grinding

- internal and external honing
- gear cutting, shaving and grinding
- machining in transfer lines
- machining on FMS lines
- deep hole drilling and boring
- broaching
- galvanic treatments
- heat treatments
- spark erosion by penetration and wire
- parts washing, and
- recuperation and treatment of oils.

A wide range of liquids is used in the metallurgical industry for cooling and lubrication duties, including:

- emulsions
- synthetic solutions
- grinding oils
- honing oils
- cutting oils
- laminating oils
- tempering oils
- kerosene
- white spirit
- washing solvents
- dielectric liquids, and
- galvanic baths.

Water is, of course, used as a rinsing liquid in many cases, but is also being used in place of some more volatile organic compounds, because of the need to cut down on VOC (Volatile Organic Compound) emissions to the atmosphere.

In the majority of cases, coolants are contained in a circulating system, either dedicated to an individual machine or in a central system supplying a number of machines. The quality of circulating coolants will deteriorate because of:

- contamination by dirt, metal fines, swarf or chips, and by foreign liquids such as water in oil-based coolants, and tramp oil in water-based coolants
- degradation by bacteria introduced into the coolant from airborne dirt, from the metal stock, and from impure water used as a diluent, and
- evaporation of water from water-based coolants, resulting in an increased concentration of dissolved minerals.

Deteriorating coolant properties can lead to loss of precision in work, reduced tool life, heavy wear on machine parts, need for frequent replenishment of coolant and an unpleasant working environment, with smells, fumes and even a risk of skin disease. Effective cleaning of the whole circulation system before new fluid is used, and effective methods of purifying and recirculating coolants, are therefore advisable, as being good housekeeping and a sound investment. Table 4.7 shows details of machining processes with their coolants and cleaning systems.

Table 4.7 Machining processes

	Cleaning system													
	Sedimentation tank [1]	Magnetic separators [2]	Strainers [1]	Paper pressure filters	Centrifuges	Sedimentation tanks with drag-out conveyor	Magnetic separators [2]	Centrifuges with automatic dicharge	Hydrocyclone separators	Bandfilter installations	Backflushable strainers	Immersion chamber filters (FaudiMatic)	Procoat filters	Combinations
Machining process	**With manual cleaning**						**With automatic cleaning**							
	Water base coolants (emulsions)													
Turning/drilling/milling	×	×	×[4]			×[1]				×	×	×		×
Machining centres						×[1]				×	×	×		×
Turning machines						×[1]				×	×	×		×
Broaching/deep hole drilling		×	×[4]							×	×	×		×
Cylindrical grinding	×	×	×[4]		×		×	×	×	×		×		×
Surface grinding	×	×	×[4]		×		×	×		×		×		×
Grey cast grinding										×		×		×
Band grinding										×		×		×
Honing and superfinish			×			×			×				×	
Cold rolling										×				
	Coolants that cannot be mixed with water (oils)													
Turning/drilling/milling	×	×	×[4]			×[1]				×[3]	×	×		×
Machining centres						×[1]				×[3]	×	×		×
Turning machines						×[1]				×[3]	×	×		×
Broaching/deep hold drilling		×	×[4]			×[1]					×	×		×
Cylindrical grinding	×	×	×[4]		×		×			×[3]		×	×	×
Surface grinding	×	×	×[4]		×		×			×[3]		×	×	×
Grey cast grinding										×[3]			×	×
Band grinding										×[3]		×	×	×
Honing and superfinish				×									×	×
Spark erosion													×	
Cold rolling													×	

1 = For low requirements, 2 = Only for ferritic material, 3 = Up to about 22 cSt, 4 = For light machining.

When correct filtration is applied, the coolant liquids are clean, and so higher production is achieved. Contaminating particles spoil the surface of machined parts because they lodge between the tool or grinding wheels and the piece of work. In grinding operations, correct filtration avoids the pores of the grinding wheel from becoming blocked, which may cause excessive pressure on the part being ground, giving rise to geometrical deformation, and also producing micro-cracks in its surface. Correct filtration of coolants used during the manufacturing process also ensures a better adhesion of surface coatings, such as titanium nitride.

Where cutting fluids are used in considerable volume, for example for groups of individual machines, centralized supply systems are often better than individual circuits (Figure 4.39). Such a system can also incorporate a centralized cleaning unit for accepting dirty coolant from the machines and returning it clean. Such a cleaning plant can be specifically adapted to the requirements of the machines and plant involved.

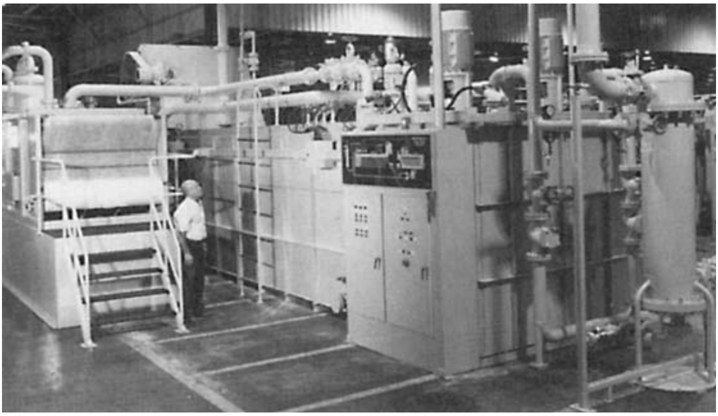


Figure 4.39 Central coolant filtration plant

Contaminants present maybe fluid or solid, and the latter may be fine or coarse, fibrous, chips, slushy or acicular (needle like), as well as varying widely in size. Grinding operations in particular produce extremely fine particles, which are not readily separated out by conventional filters. The water used as a diluent in water-oil fluids can also have a significant effect. Hard water can cause a scum to form, which will clog filters; soft water can cause foaming if highly agitated. High mineral content in water can make fluid residues more solid than when pure water is used.

Tramp oil particularly should be removed from water-oil coolants, as its presence can degrade the coolant properties dramatically, thus considerably reducing its useful life; for example, it can cause loss of cooling and wetting properties, deplete emulsifiers, nullify rust inhibitors, and impede filtration. In fact, for any particular machine there is a maximum tramp oil level that the system can tolerate, without requiring the machine or central system to be shut down for cleaning. Ideally, a system should have a tramp oil separator that ensures that the tramp oil level left in the system is always below the maximum acceptable limit for the process (cutting, grinding, etc.).

Treatment for water-based coolants

Water-based coolants are 'soluble' oils in the form of emulsions in water, with necessary additives such as emulsifiers, coupling agents (to assist dispersion), corrosion inhibitors, anti-foaming and wetting agents, and bactericides – a complicated chemical cocktail, which explains why it is important to clean and recycle the liquid, rather than throw it away when it becomes too dirty. The first step towards maintenance of water-based coolant quality is correct mixing. In a good emulsion, the oil droplets should be about 1 μm in diameter and positively charged for mutual repulsion, so as to keep them in a state of colloidal suspension.

The water used must be softened if necessary, with sodium carbonate, to prevent foreign ions from destroying the droplet surface charges and allowing coalescence. The oil must be added to the water (not vice versa) and the two liquid phases must be mixed quickly to prevent foaming and scum formation.

To maintain the coolant in a clear state, the system should provide for continuous removal of solid contaminants and allow fines to settle out of the flow stream. The solid impurities in water-based cutting coolants are generally coarser than those in, for example, grinding oils. Swarf is usually easily removed by straining and medium-sized particles by gravity settling in a dirty tank (Figure 4.40). The dirty and clean tanks are often combined in a single vessel with a system of baffles, except for

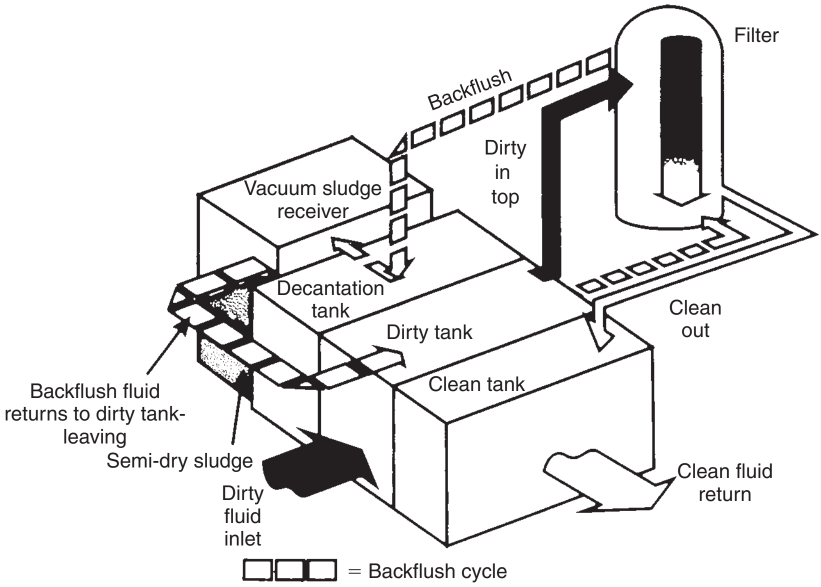


Figure 4.40 Self-cleaning coolant filtration system

applications with low stock metal removal, when the dirty tank may be skimmed or scraped by a drag-link conveyor. However, some fine particles in the micrometre range still remain in suspension, and these may need to be removed before the coolant is recycled, in order to avoid undue tool wear and impairment of work finish.

Screens, screening machines and rotary strainers can trap solid particles down to about 15 μm, have high capacities and are relatively inexpensive. Conventional filters can also perform a similar duty on low volume systems and are produced in a variety of forms to fit in both centralized and individual systems. They may also be used with, or combined with, magnetic filters to separate and retain ferrous metal particles.

Hydrocyclones are even simpler and cheaper than screens, but are less efficient and less flexible as regards to the contaminants they can handle. They are also sensitive to blockage by large particles or tramp oil. Two-stage hydrocyclone treatment can trap particles down to about 5 μm.

Centrifugal separators, of the disc stack type, offer many advantages, but are more expensive. They can be advantageously associated with screens and can remove fine particles passing through screens, as well as tramp oil. Both one and two-stage units may be employed. Figure 4.41 shows a schematic flow sheet for a coolant treatment plant including such a centrifuge.

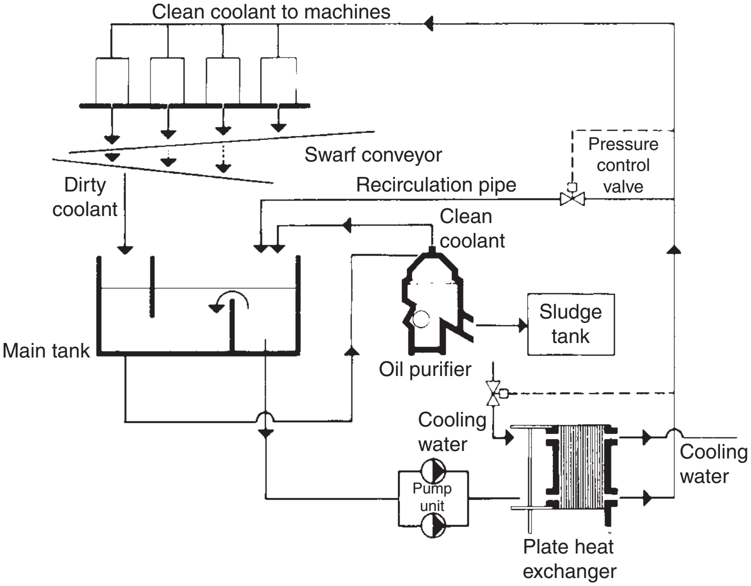


Figure 4.41 Coolant purification circuit including centrifuge

Gravity band filters, as well as hydraulic and pneumatic band filters, are among the most common items of filtration equipment used in conjunction with metal working fluids. They operate with a flat band of filter medium (at one time always paper, but now a range of nonwovens), which is drawn once across the bed of the filter, and then rolled up for disposal. They are generally simple to operate and can efficiently filter emulsions, synthetic solutions and aqueous washing solutions. The quality of the filtered liquid depends on the type of filter band used, which can range in cut size from 5 to 150 μm.

Drum filters are typically being replaced by the hanging leaf or cartridge element filter, such as the Star filter shown in Figure 4.42. In operation, contaminated coolant enters a dirty coolant tank, where heavy solids fall to the bottom and are withdrawn in a nearly dry state. The contaminated coolant is drawn through the filter elements (usually six or eight sets of two panels) where suspended solids are trapped on the element surfaces.

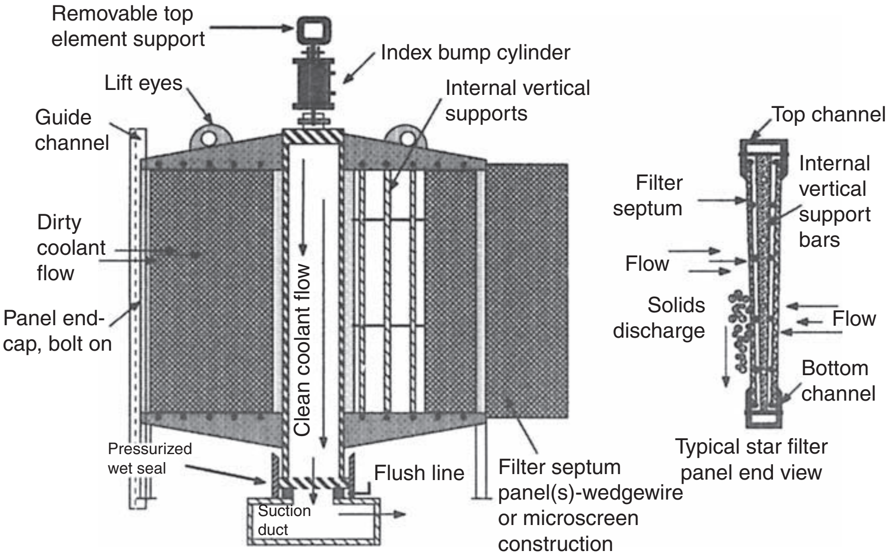


Figure 4.42 Automatic filter for coolant cleaning

Cleaned coolant passes through the element modules, and past a pressurized wet seal arrangement that eliminates the bypassing of contaminated coolant. Pressurization of the seal with clean coolant ensures that no contaminated coolant is allowed to migrate into the clean coolant section of the filter. The cleaned coolant passes on to the system's clean coolant pump, and thence to the point of use. The filter elements are regenerated by a backflow of clean coolant.

Final disposal

When the emulsion can no longer be used, it must be separated so that the two phases can be easily disposed of. Ultrafiltration of stable oil-water emulsions produces a pure water and an impure oily phase. Normally the water stream can be directly discharged to a sewage plant without any post treatment. In many cases, the oil can be concentrated by 40 to 60%, leading to a considerable volume reduction and hence reduced disposal cost. Oily wastes with oil concentrations of more than 50% can support combustion.

Detergent solutions at elevated temperatures and high pH values can be used to clean the ultrafiltration plant.

Tramp oil separation

Centrifugal separators are generally recognized as the most effective method of removing tramp oil in high volume systems, and can reduce tramp oil level to 1% or less, as well as removing solids and some emulsified oil. High capital, operating and maintenance costs are less attractive features in the case of smaller industrial plant.

Alternatives available are:

1. skimmers – wheel or belt-type, where floating tramp oil adheres to the wheel or belt, which is then wiped clean, transferring the tramp oil to a collecting drain; at best these can be expected to reduce the tramp oil level to between 2 and 3%; they will not remove emulsified or suspended tramp oil that may be present in the system
2. porous media separators – which are typically gravity-type filters with a porous medium through which water and oil permeate at different rates; they are relatively inexpensive units, capable of separating free-floating and suspended tramp oil, as well as solids, and reducing the tramp oil level to the order of 0.5 to 1.5%; they are compact in size and take up minimal floor space
3. tube bundle and lamella separators – that are basically separating tanks with nests of inclined parallel tubes or plates; they will remove only free-floating tramp oil (and some solids by settlement) with a capability, when suitably sized, of reducing tramp oil level to the order of 1.25 to 2%; their main disadvantage is the large size needed for effective operation.

The key feature of tramp oil separation is to allow enough time for the oil droplets to coalesce, or to provide surfaces upon which the oil settles. This is done on the porous media of 2, or within the tubes or between the plates of 3. A typical schematic of a tramp oil removal system is shown in Figure 4.43.

Emulsion splitting

Ultimately, even with efficient cleaning treatment, emulsions reach the end of their useful life. Disposal can then be a problem, since public health authorities in most industrial countries limit the permissible oil content of liquid wastes to be discharged into sewerage systems. These limits are typically between 10 and 50 mg/l. To conform to this, it is necessary to split the emulsions to remove the oil content before attempting disposal of both phases. If the volume involved is large, it may be economic to recover the oil to be used as fuel or even as hydraulic fluid.

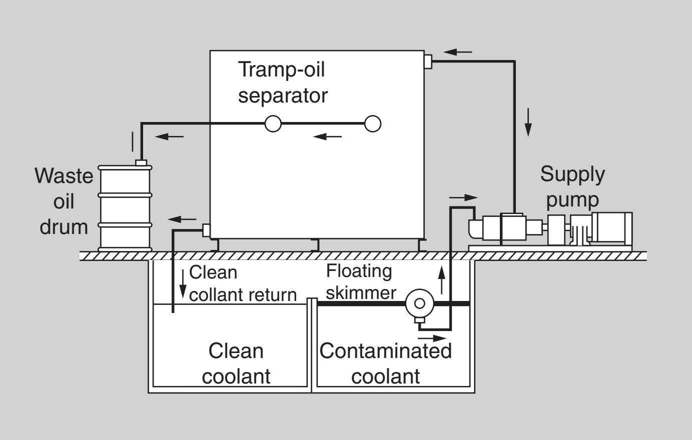


Figure 4.43 Tramp oil removal schematic

Emulsions may be split chemically (by flocculation) or by heat (phase formation). Flocculation processes produce sludge, which consequently entails the use of sludge-handling equipment. On the other hand, phase formation processes produce little or no sludge and are generally to be preferred. The sludge that emerges from phase formation usually amounts to only 0.5% of the total flow. It is formed from any emulsifying agents, cleansing fluids or similar chemicals that may be present in the emulsion – small quantities of these substances, and even relatively large quantities of free oil, do not affect the splitting process.

The phase formation method is based on the principle that, if the electric charges that keep the oil droplets apart are reduced or eliminated, the droplets will agglomerate, forming larger drops. This is achieved by adding a strong electrolyte, such as 2 to 3% of a saturated solution of magnesium chloride, and then mixing the solutions as they are heated up to a temperature of 98°C. At this temperature, the surface tension is very low and the droplets quickly coalesce, becoming larger until the emulsion splits into an oil phase on top of a water phase. It should be noted that treatment with a solution of a salt will not split purely synthetic emulsions, i.e. emulsions containing aqueous solutions of alcohols and esters, etc.

Electroflocculation is a purification and de-emulsification technique that is of growing importance. It is a combination of the processes of electroflotation and electroprecipitation, and it is claimed that electroflocculation may remove finely dispersed particles or droplets (of oil, heavy metals or organic substances, for example) from oil-in-water emulsions. Electroflotation is a flotation process in which the gas bubbles are of hydrogen, generated at the cathode by the electrolysis of water. Electroprecipitation is a flocculation process where metal ions are released from the anode. These ions collide with the suspended particles and adsorb onto the particle surface, neutralizing any charge on the particle. These two techniques, electroflotation and electroprecipitation, have a synergistic effect when combined.

Coolant treatment process design

The design of coolant filters and separators for machine tool fluids is an extremely complex and varied subject. Some of the general aspects that have to be considered before a preliminary appraisal can be made are:

1. the purpose or necessity of the filter or separator
2. the viscosity and associated properties of the coolant to be filtered
3. the metal cutting functions involved in the process
4. the degree of separation required
5. the coolant flow rate required
6. the filter capacity
7. the machine tool type and its physical characteristics relating to outlet heights, operations, table size, etc.
8. the type and nature of stock produced
9. the space available for the system
10. the expansion rate of cut material, which will convert the solid material removed into the expanded volume of chips, swarf and slurry, etc.
11. the target system efficiency and cost-effectiveness in terms of total stock introduced related to that remaining in suspension after complete cycling
12. the operating period affecting stability of production and flexibility and durability of the system
13. any protective devices to be incorporated in the system to cover misuse or mechanical failure, and
14. the safety of the system, ensuring that it complies with at least the minimum standards laid down by the relevant Health and Safety legislation.

Filter appraisal

Provided all the relevant information is available, the process of individual assessment of the stages necessary for the system can be undertaken. In this analytical process of breaking down it is possible to determine, by selection and elimination, the number of stages required, and the size and types of filter media best suited to provide a filter that invariably must combine several distinct functions.

The range of machine tools presently under production is diverse and extensive. The designer's function may thus vary from specifying equipment for a single, small tool-room grinder, up to that for a complicated multi-stage unit requiring detailed site appraisal, in addition to a special study of the requirements of individual machines. The latter could call for a central treatment system serving either a line of machines, or complete section of the working plant. Safeguards will also be necessary on a central system to avoid the production losses that could result if the system is not fully equipped with full standby pumps, auto-level monitors, alarms, and backup systems to cover electrical or mechanical failure.

The design process is best illustrated by examining a typical machine and its functions. The example chosen for this purpose is a multi-spindle rotary indexing machine, using a water-based soluble coolant, machining an EN8 vehicle component, and having a variety of drilling and spot-facing operations, with one final burnishing station. The design analysis would then involve the following steps.

Purpose and need for filter

An automatic rotary indexing machine is a very expensive piece of equipment and, for an extended tool life and reduced tool wear, an optimum separation level is required in the coolant treatment plant. In addition, such a machine can be adapted to take various machining heads, from plain drilling, ejector or gun drilling, to fine boring and burnishing tools. This possible variety of configuration determines the positive need for a filter with two distinct levels of separation for the case under discussion.

Coolant

The coolant to be filtered is a soluble water-based emulsion and all relevant properties are taken into account when assessing the most suitable materials, pumps and separating devices, which may be affected by its viscosity, or any change in properties due to temperature variations, etc.

Metal cutting operations

The cutting operations consist of primary stock removal from drilling operations, using chip breaker drills, and the use of standard spot-facing tools and burning tools, the last of these producing a negligible fraction of the total stock for disposal.

The degree of separation

An optimum cut-off of 15 μm is assumed, based on an operating efficiency of 98%. The degree of cut-off required for the special burnishing station will be determined by the surface finish specified, or the particle size stipulated, by the tool manufacturer. Often the requirements are compounded by the need to provide a higher pressure coolant feed to the burnishing station, the system pump for which may have operating parameters needing a cut-off of perhaps 10 μm. Two levels of separation are thus needed, one for machine tool and single point cutting operations, and a second for the specialized burnishing tool and its supply pump.

Flow rate

The flow rate is dependent upon the number of spindles, the proximity or clustering of drills at certain positions, plus the general configuration of tooling positions and sizes. The total flow can be established by making individual spindle and station assessments, and extending these to cover all stations requiring coolant. This provides the basis of the flow required for machining operations. The total will probably be some 6.5 l/s, made up of just under 1 l/s for burnishing, with the balance for drilling operations, etc. To ensure clearance of fixtures and machine slide-ways from swarf on a machine of this size and complexity, a suitable safety factor would be a figure of 20 to 25% increase on the calculated flow, giving a total flow requirement of approximately 8 l/s.

System capacity

System capacity is directly proportional to flow. The optimum, established many years ago, was a ratio of ten units of capacity for every one of flow per minute, i.e. for every

8 l/s of flow (480 l/min) a capacity of 4800 litres was required, giving a settlement period of ten minutes. As the development of filters progressed, and machine speed and production rates improved, this cycle time was dramatically reduced. The premium attached to floor space and the cost of oils, together with improved methods of processing, have made it possible to reduce the ratio to levels as low as three to one on the first stage, or a capacity of 1450 litres. It must be stressed, however, that space permitting, or in larger underfloor designs where much higher initial losses occur, a ratio of ten to one should be maintained whenever possible.

In addition to the 1450 litres, additional capacity for clean liquid storage must be provided. The system under study has both a low and a high pressure pump drawing on the total 8 l/s cycling to the machine tool, of which 0.8 l/s is rated at a cut-off of approximately 10 μm, with the balance rated at a nominal 50 μm. To house two pumps with different levels of separation requires two holding tanks. The capacities of these, again, are directly related to system pump flow. However, in each of these tanks, the same principles of settlement occur, so that extremely fine particles may remain in suspension due to space limitations. The ratio of such storage reservoirs has been reduced where possible, thus producing a fairly rapid turnover. The high pressure pump tank capacity will still be based on a ratio of ten to one (on 48 l/min), providing a capacity of 480 litres. This has been determined because the pump is a low flow unit but operating at high pressure, and is, therefore, likely to be fitted with a high kilowatt rated drive motor, thus being a potential heat source. The ratio for the low pressure holding tank is not so critical and a ratio as low as two to one side can be used, giving a low pressure capacity of 865 litres. With a dirty tank of 1450 litres, this clean tank capacity of 1345 litres gives a combined capacity of 2800 litres.

Machine type

The machine bed size, shape and configuration will, together with the outlet height, determine first the dirty tank depth, to be taken as 600 mm, providing sufficient depth for an above-floor system for a compact holding tank layout. The feed pipe work, nozzle and ring main supply pipe work will provide information to determine liquid flow losses which will, in turn, assist in selecting pump duty ratings. Unit configuration can vary to suit the available space, but alternative rectangular or delta forms can be provided, and invariably the overall length and width of the system are determined by, and vary according to, site conditions without compromise to the already determined capacities and flows.

Nature of stock

The material is a machinable EN8. Approximately 95% by volume of stock will be produced by the various drilling operations. Chip breaker tooling has been specified so that about 95% of the stock produced will be as uniform chips, the balance being made up of small stringy segments and extremely fine particles. The nature and volume of the chips will determine that the primary system will require some means of clarification, while the finer particles determine the necessity for some kind of secondary separator.

System space

In order to keep costs low, wherever possible systems of cuboid modules should be selected. However, the design may be altered by a reduction in length with appropriate width increases. The system designer has, within the parameters of machine layout and site location, certain flexibilities that can be used when necessary. The various options should be carefully considered, and a layout adopted which least compromises the unit efficiency.

Expansion rate of material

The majority of stock is producing drilling chips of fairly uniform character. From this can be determined the volume of stock produced, by using accepted expansion ratios. If chip breaker drills were not being used, then an expansion ratio of 80:1 could result. However, because of the relatively uniform nature of the chips in question, a ratio of 50:1 may be utilized, i.e. for every 1 cc of metal removed, the filter will receive 50 cc of steel chippings.

Optimum efficiency

It has been shown that the machine requires a separator device, which is automated to some extent. The cost-effective selection has already been partly covered by the decision to have two levels of separation, rather than rating the maximum system flow at the lowest level.

Operating period

Operating period and duration affect selection of electrical control equipment and motor rating. Where possible, all of these parts of the system are specified for continuous operation. The operating period will further affect ultimate settlement during the shut-down period, and timing delays can be fitted to the primary section to ensure overloads do not occur on recommencement of operations.

Protective devices

All motors, contactors, and the mechanical overload torque limit on geared reduction units fitted to a conveyor drive unit, incorporate integral switch gear, in order that mechanical stoppage is monitored by visual or audible alarms. Low level switches also monitor sudden level drops, giving adequate warning to the operator to enable corrective procedures to be implemented.

System safety

System safety in the UK, for example, is guided initially by the statutory requirements of the Health and Safety at Work Act 1974, and must in all respects comply with the minimum requirements of the Act, together with the more recent innovations, which are continually being incorporated.

Filter selection

It can be seen that all of the basic necessary information is available to commence selection from the various types of systems that are available. Just as the simple drilling machine produced in 1948 has progressed to a multi-spindle machine with a variety of almost fully automated operations, so have its settling tanks and suds pump evolved to a multi-stage system. The precise selection of the plant components will be determined by their suitability in each case.

For the design, the stages must be analysed from machine output to the first stage of the filter, the primary tank. The requirement is first and foremost to remove a high percentage of solids in order to provide satisfactory levels of secondary and final stage filtration. The movement options are:

- a slat conveyor
- a magnetic conveyor
- a drag conveyor, and
- a belt medium conveyor.

The best suited of these on an efficiency and cost-effectiveness basis is the drag conveyor, which, due to the stock density and type of chip form, will provide an efficient removal device, raising solids up the conveyor incline and allowing adequate time for coolant drainage. Stock is discharged from the conveyor in a semi-dry state, thus reducing oil loss from the system and producing easily handled waste.

The second stage of separation offers several alternatives: thick media pressure filter, pleated paper roll filter or cartridge, strainer, or hydrocyclone. Only the last, the hydrocyclone, does not require preventative maintenance or utilize consumables, and so seems the best choice, especially from the point of view of flexibility. The hydrocyclone is also extremely durable, due to the abrasive resistant nature of the normal material of construction, namely polyurethane, together with its high impact resistance, frequently necessary in a workshop environment.

From here the coolant flows to a clean liquid storage tank, but prior to feeding coolant back to the machine tool there is one other level of separation to provide for, namely the 10 µm cut-off required for the burnishing station. For this it is necessary to fit a feed pump supplying the third and final stage of high pressure operation.

The alternatives available here are a random fibre element filter, or an inline cartridge filter fitted with elements of pleated paper or extended life stainless steel. Both pleated paper and stainless steel provide a positive cut-off. From these options, the most suitable is the pleated paper cartridge filter and, therefore, the final stage filtration is by means of a pleated paper cartridge vessel, with optional stainless steel element if required. Because of the need to be able to maintain the filter, the final stage filter will be provided in duplex form with rapid change-over valves, in order that element change can be undertaken without high pressure pump flow interruption.

The final design decision is that of determining the pressure required from the low pressure feed pump. The determining factors here are primarily the number of spindles, the size of feed nozzles, the drops and beds, and the size of the ring main pipework feeding the various tool stations. From these, a theoretical frictional loss can be calculated, which can be allowed for when making a final pump selection. These all suggest a low pressure feed pump of 7 l/s at an operating delivery of 1.7 to 2 bars.

4I. DEWATERING AND FUEL TREATMENT

Sludge dewatering

Industrial effluent is commonly in the form of a sludge that may have a variety of constituents:

- colloidal matter (organic activated sludge)
- semi-colloidal matter (metallic hydroxides)
- fibrous matter
- coagulated solids and particles (granular sludge)
- crystalline products
- coarse solids (sandy or gritty sludge), and
- mixed, miscellaneous foreign matter and rubbish.

In most cases it is advantageous to thicken or concentrate the sludge before mechanical dewatering – and it is always advantageous to dewater mechanically before any thermal drying. Thickening methods include chemical treatment, gas flotation, gravity thickening, and centrifuging. Gravity thickening is usually the most economic process, normally boosted by polyelectrolyte agglomeration – although excessive usage of such agents can reduce the efficiency of subsequent filters.

Dewatering of thickened sludges is then employed to reduce haulage or disposal costs. Until relatively recently, many industrial sludges were only dewatered to a level sufficient to make them disposable by incineration. With rising energy costs, incineration should only be undertaken with energy recovery, or alternative methods of disposal become more economic and necessary, certainly in any case where the dry sludge is not combustible. The bulk of a sludge to be disposed of can be substantially reduced by mechanical dewatering (so making long distance transport more feasible). For example, starting with a sludge containing 1% (dry weight) of solids, dewatering to 25% solids gives a volume reduction of 88%, dewatering to 30% solids – a volume reduction of 90%, dewatering to 40% solids – a volume reduction of 92.5%, and dewatering to 50% solids – a volume reduction of 94%.

Equally important as dry volume is how the dry cake packs together in a truck for transportation. A very dry cake (e.g. 50% solids) is easier to handle than a slimier cake (e.g. 25% solids), but may in fact represent a greater truck volume, because it does not pack down so well. The actual volume reduction between the cake at 25% solids and that with 50% is only 6%, and this may require considerable extra filtration or separation effort and cost.

The two basic methods of dewatering are by filtration and sedimentation. The nature of the sludge, together with the volume to be handled, are important parameters in selecting the most suitable method of dewatering. Several types of filter can handle most sludges and many can provide filtration at different pressure levels, which can be an advantage when handling sludges containing a high proportion of solids. Rotary drum vacuum filters, filter presses and belt filters are widely used for sludge dewatering. These are available in a wide range of sizes. The firmer the sludge and/or the more fibrous it is in nature, the wider choice of suitable filters.

Sandy sludges and those containing coarse solids can often be dewatered quite satisfactorily by simple screens. Pressure filters are then not necessary, unless there are other constituents present tending to produce a binding cake.

With sedimenting separators the choice lies broadly between gravity separators (settlement tanks), with or without coagulation units, and centrifuges. On a volume basis, the former are best suited for handling large sludge volumes economically (although at a high land use), whereas a centrifuge can give greater separation with smaller volumes, but consumes power all the time it is providing throughput. Centrifuges are also not generally suitable for handling shear-sensitive sludges, as they will then generate a dirty centrate, which may need further filtration or separation treatment.

Large-scale sludge treatment plants are necessarily tailored to specific requirements, and are normally designed for continuous operation and to be automatic in use. A variety of filter-separators may be employed in the complete system.

Coalescing plate separators

Coalescing plate separators are used on board ships to control pollution from bilge water discharges, also as a means of preventing the pollution of drains and rivers from oil spillage and rain water run-off from factories and petrochemical installations. A typical example of such a separator is shown in Figure 4.44 to consist of a horizontal tank, containing an array of closely spaced, flat or corrugated plates, mounted close together and at an angle close to horizontal. The plates are made from oleophilic polypropylene and the flow of liquid between them is laminar. This flow pattern in the oily

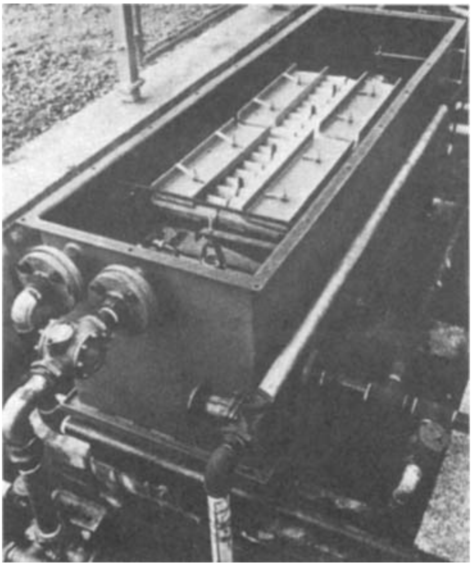


Figure 4.44 Coalescing plate separator

water mixture causes the oil droplets to rise due to the difference in specific gravity between the oil and the water, until they attach themselves to the underside of the plates. They then coalesce further on the plate surface, and rise through weep holes to the surface of the unit, where the oil layer that forms can be removed by a skimmer. This type of separator is capable of removing droplets down to 7 μm in size.

Effluent separators of this kind can reduce the oil content of the effluent discharge to better than 15 ppm. The units can operate by gravity flow or incorporate a low shear inlet pump depending upon the application. They can also be pressurized to retain the oil vapours.

Coalescing plate separators allow water ballast to be discharged in-shore and on the high seas without risk to the environment and without detectable oil slicks. In standard form they reduce the oil content of discharges to better than 15 ppm, and all oil droplets discharged are smaller than 20 μm and are thus quickly degraded by seawater. The recovered oil normally has a water content of less than 3% and can be used as furnace fuel without further treatment, or can be reprocessed.

Bilge water separators

All ship operations have to comply with an IMO recommendation that the maximum permissible oil content in bilge water discharges is 15 ppm. Marine bilge water discharges are similar whatever the ship. A typical separator specifically designed for fitting into small sea-going vessels is able to reduce the oil content to better than 15 ppm without the use of cartridges, and to maintain this performance automatically for concentrations of oil in the water of up to 25% on a continuous basis.

Fuel washing

The marine diesel engine must be kept running for long times and over long distances, without calling in port for maintenance. It is necessary for diesel fuel and gas oil to be washed continuously before burning, and this provides good business for the makers of liquid fuels washing systems, to remove sodium by water washing, and then to separate the water and fuel. Packaged systems are the norm for maritime use, and these can employ cartridge filters, or parallel plate separators, or disc-stack centrifuges as the main separating unit, with strainers ahead of the separator to remove sizeable dirt.

The packages are generally installed between the storage or settling tank and the daily service tank. A pump continuously transfers sufficient fuel from tank to tank to keep the daily service tank full. The main separator is then fitted on the outlet of the pump to remove the dirt and water. An automatic water drain and alarm system is connected to a level control in the filter-separator to keep the water level in the water collection areas of the separator between an upper and lower set-point by opening and closing a solenoid drain valve. Should the fuel be suspect and contain large quantities of water beyond the drain capacity of the valve, then an alarm will be raised.

Aviation fuel treatment

Where aviation fuel treatment is concerned API and military specifications for quality apply. Where the fuel is heavily contaminated by suspended solids, the use of a micro-prefilter will extend the life of any coalescer cartridge and reduce operating costs. Where it is necessary to treat surfactant laden and discoloured fuels from multi-product pipelines, clay and fuller's earth filters are used.

Generally, vertical or horizontal coalescer-separator vessels for fuels are fabricated from carbon steel, coated internally with various linings such as epoxy resin. Applications include their use in refuelling facilities around the world, helicopter and VTOL support bases, with large capacity units used for bunkering or fuel distribution depots.

5

OILS AND HYDRAULIC SYSTEMS

SECTION CONTENTS

5A. INTRODUCTION

This section of the Handbook is entirely devoted to the utility filtration applications involving machinery fluids – mostly to do with those used in engines and hydraulic systems. Some of the subject matter has already been covered in Section 4, but it was done there from the point of view predominantly of aqueous fluids, whereas now the emphasis is on the treatment of oils.

The subject matter of this section is also largely concerned with liquid filtration, but coverage is included of engine air filtration for the sake of completeness.

5B. ENGINE FILTERS

The engines used in automotive vehicles of all kinds, and as stationary power sources, consume air and liquid fuel as their energy source, and rely on liquid lubricant and coolant to maintain them in good condition. Another fluid – the exhaust gas – is currently of considerable environmental concern, as a source of atmospheric pollution. So there are five fluids involved in the operation of an engine, all needing filtration for one reason or another:

- the incoming air and liquid fuel must be filtered to prevent contaminants in them from getting into the engine

- the coolant and lubricant (especially the latter) pick up contaminants from inside the engine during its operation, and these must be removed before they can cause harm to the engine, and
- the exhaust carries the products of combustion, especially unburned carbon, which are harmful in the human environment and so should be removed before the exhaust gas leaves the immediate surroundings of the engine.

The first four of these filtration requirements are fully mature, having been recognized as necessary from the start of the history of the engine. Whilst by no means being an unchanging technology, air, fuel, coolant and lubricant filtration has become a standard application, for well established items of equipment (Figure 5.1). Exhaust filtration, on the other hand, has really only become an item of concern in the last twenty years or so, and a subject for regulation in the last ten. It is a fast developing technology – but the 'goalposts' are moving fast as well, in terms of the permitted size of contaminant particles in the exhaust.

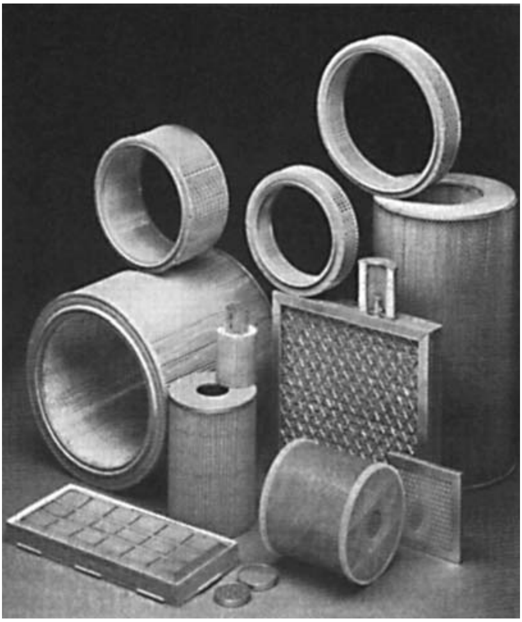


Figure 5.1 A range of engine filters

As with every other field of human endeavour, the demands of modern society are making the operation of engines of all kinds more difficult. Ambient air is dirtier, especially with the products of engine combustion, or engines are used in less amenable places where the air is intrinsically more of a problem – desert areas, where the air is full of sand, or littoral and off-shore installations, where the air is laden with salt spray. Demands on the engine are more stringent, temperatures are higher, equipment life expectancy is increasing, permitted contamination in the exhaust is decreasing, engines are getting bigger – all of these make the job of the engine filter that much more difficult, especially as the engine builder has no control over where the engine will be used. It follows that engine filters need to meet the demands of a world market, with a varying set of operating environments and fuels.

The several filters associated with a particular engine have to cope with very different conditions. Intake air and liquid fuel filters operate at ambient temperatures and pressures, on a once-through basis, taking in either ambient air, of whatever local quality, or fuel, of whatever quality the supplier provides (including any contamination picked up between the delivery point and the engine). Engine coolant and lubricant, on the other hand, must work at higher temperatures, on a continuously recirculating basis (because they are both too valuable to throw away), with a contaminant level arising mainly from wear within the appropriate flow circuit, a level that will steadily increase unless some separating device is included in their circuits. Finally, the exhaust stream is very hot, and is laden with combustion products as well as some corrosion and abrasion products from within the engine. These duties all require fine filtration, with a demand for ever finer degrees of separation, so as to get a better performance and a longer life from the engine.

Very large engines, on vehicles, stationary land-based installations, aircraft or ships, let alone power stations, are mainly supplied as gas turbines. These obviously have fewer filter applications, because of the absence of a liquid fuel, but they place very severe demands on the filters that they do use, because of the very high rotational speeds. They are reviewed in Section 6.

Liquid fuel filters

Automotive fuel delivery and fuel filtration systems are evolving rapidly with polyester depth filter medium playing a prominent role. In addition, a graded density polymeric depth filtration medium is used in a six-layer sandwich configuration, consisting of a square weave nylon cloth layer, a spunbonded nylon layer, three layers of polymeric depth medium, and a layer of spunbonded nylon, for use as in-tank fuel filters. With its multi-layer configuration, this relatively new medium allows the filter to trap progressively smaller debris throughout the layers of the filter material.

Diesel engines in particular are dependent on having clean fuel available at the pump and injectors, so that fuel filtration becomes as important as lubricating oil filtering.

Petrol engines

Contaminants in engine fuel can clog or partially clog jets, and drilled or cored passages in the carburettor, upsetting their metering performance and causing loss of power, poor starting characteristics, or even damaged exhaust valves through overheating, produced by an excessively weak mixture. Quite small particles may lodge on the seat of the needle valve, causing the carburettor to flood. Abrasive particles may abrade the accelerator pump seal or score valves or valve seats. There is the further consideration that abrasive particles carried through the carburettor and into the combustion chambers may result in scoring of cylinder walls or loss of efficiency of piston rings.

Provided normal precautions are taken when filling the tank, few contaminants should be introduced at this stage. The possible exception is water, which is always likely to be present in small proportions in pumped petrol. The main cause of fuel contamination is corrosion or deterioration of the inner surfaces of the tank itself, or the redistribution of foreign matter already in the tank.

Coarser particles can be retained in the tank by a coarse mesh strainer fitted in the tank at the outlet point. Water will settle to the bottom of the tank and would not normally be drawn up if the outlet pipe is positioned correctly, and even if it is drawn up, the coarse strainer is reasonably effective in arresting it. Most tanks have strainers and additional protection provided by an in-line disposable filter on the entry side of the fuel pump, together with a settling or sediment bowl on the pump inlet. Further protection is usually provided at the carburettor or fuel injection system entry point with other simple strainers.

If the fuel delivery is screened at the point of entry to the fuel pump, this dispenses with the need for a sediment bowl. In the recent past, in-line filters mounted between the pump and the carburettor consisted of a nylon cloth, porous ceramic, sintered bronze or phenolic resin-impregnated paper element, while in-tank filters were made of saran or saran-polyester cloth. The size of the filter needs to be fairly generous, as relatively high flow rates may be involved with large capacity engines operating at maximum speed (when fuel delivery requirements are most critical).

To assist in assessing the condition of the filter, the body was often made in transparent plastic (such as nylon) or glass. The contaminants to be looked for included both dirt and water. The paper element needed to be resistant to both petrol and water. Working pressure was very low, so little support was needed for the element. Typically, flow was arranged from the outside to the inside, with the element simply located in a housing. This was normally connected to the fuel line at each end by short lengths of hose.

Current fuel injection systems use both in-tank and in-line fuel filters. These systems use a rotary electric fuel pump, mounted in the fuel tank, with the filters made of nylon cloth to cope with the increased heat generated by the pump. In-tank pumps operate continuously at their maximum flow capacity when the engine is switched on. Depth filter media can double the capacity of automotive fuel filters, trapping contaminants in the depth of the medium, rather than just on the surface like conventional cloth filter media.

Diesel engines

In the case of diesel engines, the need for effective fuel conditioning is essential to protect the highly sophisticated fuel pumps and injection equipment. Main filters, prefilters (sedimenters), fuel heaters and hand primers are needed to keep fuel flowing under the harshest operating conditions. The most damaging contaminants to fuel injection systems are abrasive particles in the 5 to 20 µm range. The critical areas for wear in in-line pumps are delivery valves and pumping elements. The distributor rotor is equally crucial for rotary pumps. Water, as well as dirt, can be present in diesel fuel and this can have the same disastrous effect on the fuel injection pump as dirt contamination. Waxing can also mean blocked fuel lines, clogged filter elements and a general deterioration of the engine caused by starting difficulties.

Before the selection of the most appropriate fuel conditioning equipment, the worst operating conditions that will be encountered must be identified, together with any special requirements. The key operating factors and areas of consideration for diesel fuel filtration are listed in Table 5.1.

Table 5.1 Diesel fuel filter operating factors

Operating factors	Considerations
Fuel flow	Engine full load/speed consumption plus fuel recirculated to tank.
Fuel contamination	Fuel quality/storage/handling. Operating environment. Condensation/atmospheric conditions. Operator custom and practice.
Lowest operating temperature	Lowest ambient temperature. Vehicle/plant overnight storage. Chill factor on exposed equipment. Fuel quality/waxing temperature.
Highest temperature	Highest ambient temperature. Proximity of exhaust system. Ventilation. Vehicle/plant production (e.g. stove painting).
Vulnerability to damage	Mounting positions. Likelihood of abuse/damage from stones, etc.
Safety/protection features (water warning/engine shut-down)	Operator conscientiousness. Variability of fuel quality/contaminants. Operating environment. Fuel handling. Safety (engine shut-down).
Servicing periods	Cost of service. Availability of vehicle/plant for service. Operating periods. Quality of services.
Application	Legal requirements/construction and use regulations. Safety.

A well-designed diesel automotive fuel system is shown in Figure 5.2. The positioning of equipment can be critical to performance, but, as a general rule, where fuel contamination is likely to be small, standard type filters with either single or twin bowls can be used. These are specifically used as main filters to protect the fuel injection equipment and usually contain paper elements with high burst pressures and the ability to withstand the large pressure drop that can exist across the filter when high performance feed pumps are used.

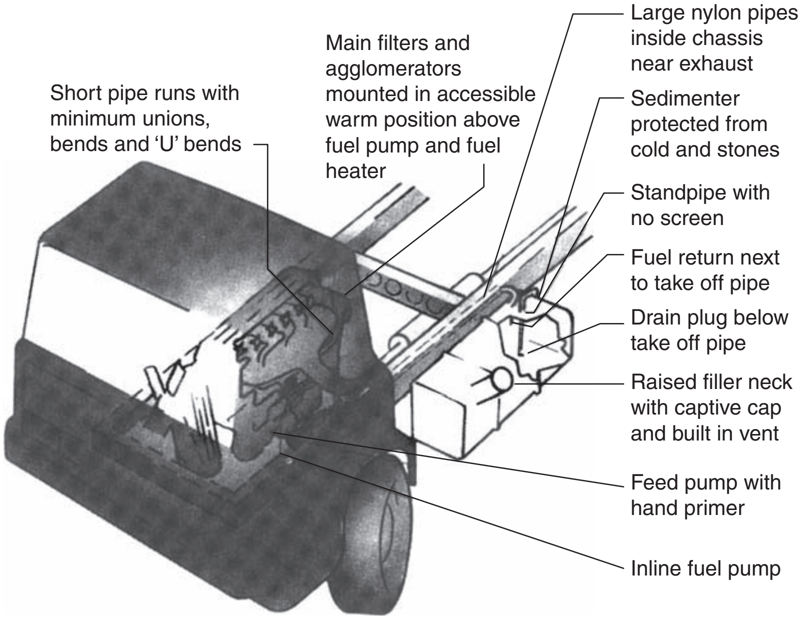


Figure 5.2 Diesel fuel filtering system

In the selection of diesel fuel filters, it is important to verify that they have been tested in accordance with the appropriate ISO test standard, which measures the effectiveness of fuel filters.

Sedimenters are prefilters that separate water and other contaminants out of the fuel by sedimentation. Sedimenters should be mounted as close to the fuel tank as possible and before the feed pump.

Agglomerators are fitted on the pressure side of the feed pump. They are also used to separate water from the diesel fuel. The fine pores of the filter paper isolate and retain solid particles, while fine water droplets are forced through the pores and agglomerate into large droplets, which are then deposited by sedimentation into the bottom of the unit.

Figure 5.3 shows a typical fuel circuit for a diesel engine with its fuel injection pump and a filter-water separator, such as is shown in Figure 5.4.

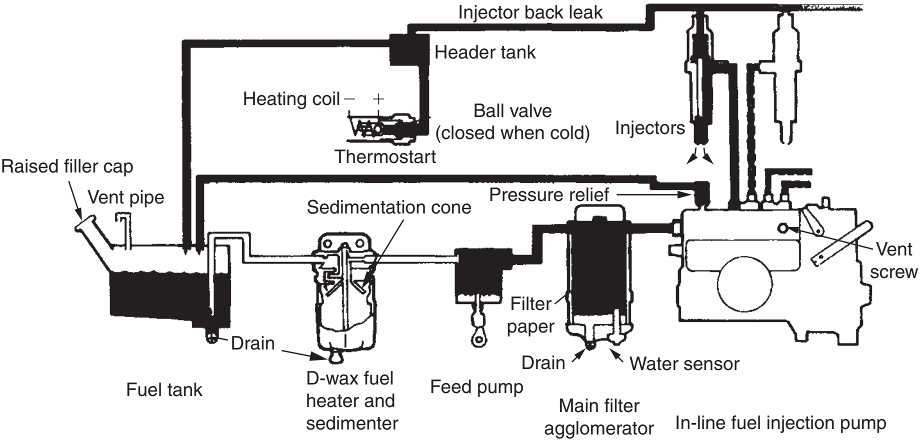


Figure 5.3 Diesel fuel filtering circuit

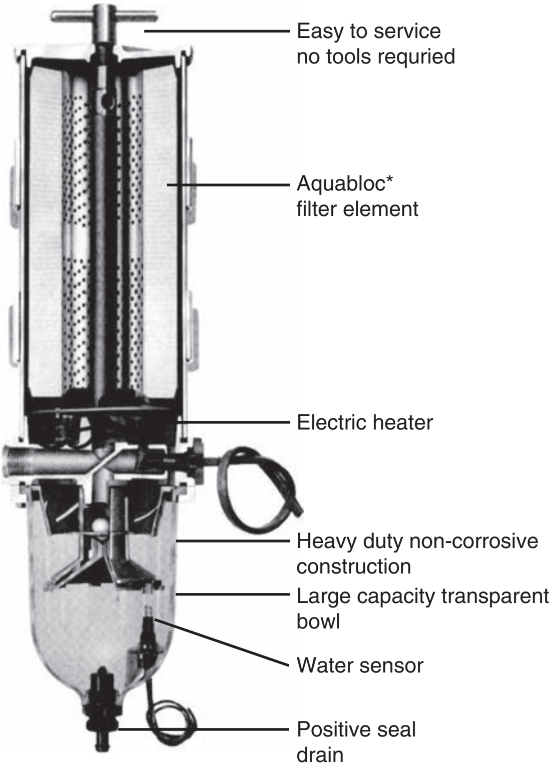


Figure 5.4 Diesel fuel filter-water separator

Heavy fuels

Heavy fuel oils are mainly used in land-based engines or marine engines, where there is space (and the ease of mounting) for a large filter, necessary to deal with the higher viscosity oil. A full-flow duplex filter, designed for use with heavy fuel oils is shown in Figure 5.5. A changeover valve allows either one element or the other to be in use, provision being made for priming the standby element while the in-use element is carrying the full flow. With the valve in the mid position, fully opened ports allow both elements to operate in parallel.

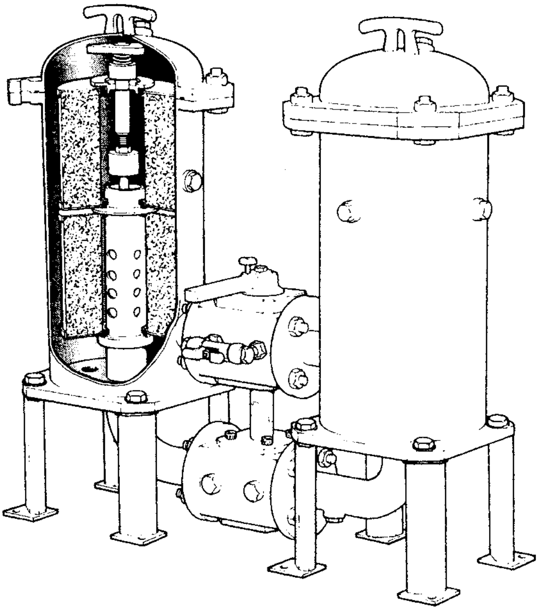


Figure 5.5 Duplex fuel oil filter with changeover valve.

Duplex filters are designed for use where an uninterrupted fuel flow is required, or where an immediate standby filter is essential. Fuel oil filters can generally incorporate air vents, drains and tappings for pressure differential instruments. Steam jackets, magnetic elements and interlocking safety devices may also be fitted. Fuel oil cartridges for this type of filter are fitted with media capable of operating up to 160°C, with a 4 μm nominal filtration efficiency, and can withstand a 10 bar pressure differential.

Air filters

The quantity of air inducted by internal combustion engines is vast. Something like 10,000 times the volume of air passes through a petrol engine for each unit volume of fuel. Since atmospheric air is seldom clean, unless intake air is filtered, the possibility of inducting a considerable mass of solid contaminants is obvious.

Since an engine is essentially an air pump, its efficiency is affected by the suction conditions, calling for a low pressure on the inlet side. This in turn means that the filter size will be large and that it preferably has low pressure drop characteristics. The large size can be turned into an advantage in that it is possible to use the body of the filter as a resonant chamber, to act as an intake silencer. Thus, the body can be, or should be, designed as a low pass acoustic filter, at levels well below engine frequency, with the element acting as a mechanical filter for the air. Solutions which have been adopted actually vary from one extreme to the other: from efficient acoustic filters with poor or indifferent mechanical filtration, to efficient mechanical filters with little or no silencing effect. Equally, on vehicle engines, size may be too restricted (affecting engine performance or fuel system calibration) or unnecessarily large, therefore requiring a bulky and possibly heavy structure to be rigidly supported above the engine.

Originally, the oil-wetted filter was widely favoured for air intake filtration. Effective filtering with such types, however, depends on their having a uniform degree of wetting of the wire mesh with oil, which is seldom achieved in practice. Even so, the oil bath air filter is still in common use.

A variation on this type is the polyurethane foam cartridge housed in a simple container. This consists of an oil-impregnated cartridge to provide mechanical filtering, with the oil held in the pores of the foam trapping the dust as the air passes through the filter. Whilst more consistent than the wire mesh type, the efficiency of filtering, and to a lesser extent the actual pressure drop through the filter, still depend on the uniformity of the oil application. If the cartridge is allowed to dry out the practical filtering effect can be virtually nil.

Most modern air filters use pleated paper and synthetic fibre elements, with the element employed in the form of an annular cartridge, with the flow from the outside to the inside. Contaminants are thus collected on the outer surface of the pleats. Such an element can be restrained by end rings, and further stabilized by inner and outer perforated metal tubes or wire screens. The complete element or cartridge is then simply mounted inside a suitable container, the shape and form of which may vary considerably.

For simple air filter duties, without silencing, the cartridge may itself form the complete filter. This sort of design would be used primarily as a crankcase breather filter, or a filter on a hydraulic reservoir breather. It may also be used as an intake filter on very small internal combustion engines, because of its simplicity, low cost and low pressure drop. The complete filter is then replaced as a unit when clogged.

For general air intake filtering duties, without silencing and up to flow rates of the order of 350 m^3/hr, a cowl type is commonly preferred. With this type, it is usual for the cover to be held by a screw or nut, so that it can be removed to replace the cartridge when necessary. For higher capacities, the body or casing normally becomes a permanent fitting, mounted to the engine intake, with a detachable lid to facilitate removal of the cartridge.

Where silencing is required, it becomes necessary to increase the volume of the unit, typically by increasing the diameter of the filter element or annulus, without necessarily increasing the depth of corrugation, or even reducing this depth because of the greater surface area and also to add extra volume outside the cartridge, if necessary.

There are numerous variations on these themes. Some engine manufacturers may adopt standard filters, others employ special designs. Ducting may also be incorporated to provide feed air through the filter from the most suitable point, as well as to increase the effective volume of the intake resonant chamber. It is sufficient to repeat that many intake filters are of the pleated paper element type, with a replaceable cartridge. Unlike oil filters using a similar element, paper elements for air filtration can be cleaned utilizing a backflow of compressed air. Some may even be specified as suitable for cleaning by backwashing with a suitable solvent. It is normal practice, however, to replace the cartridge rather than to clean an air filter element.

Dry air filters/cleaners

Generally dry air filter/cleaners tend to be either single stage or heavy duty, with or without precleaners. Integral precleaners can remove up to 96% of the intake dust before it reaches the filter element. The pre-extracted dust is either collected in a dust collection bin fastened to the cleaner's housing or discharged through dust discharge ports. A typical single-stage dry air cleaner is shown in Figure 5.6.

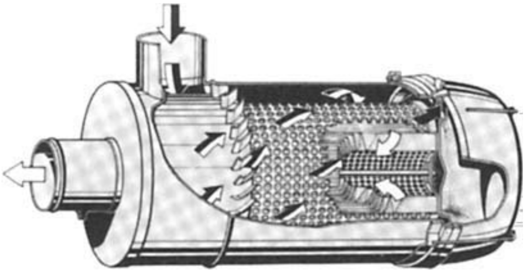


Figure 5.6 Engine air intake cleaner

Single-stage dry air cleaners are suitable for light to medium dust conditions on such applications as road vehicles and electric generators. Heavy duty units are intended for use under heavy dust conditions, such as those found on construction sites and construction and agricultural equipment. Heavy duty cleaners for large tracked vehicles and for heavy construction equipment often incorporate multi-cell cyclones to act as precleaners.

At the other end of the engine, the need to clean exhaust flows is growing rapidly, especially for diesel engines. For stationary engines, sintered metal particulate filter traps can reduce soot emissions by up to 98%. Essentially, these traps are volume filters that consist of sintered stainless steel filter plates assembled into units of varying sizes. On smaller engines, silicon carbide filter elements are used (Figure 5.7).

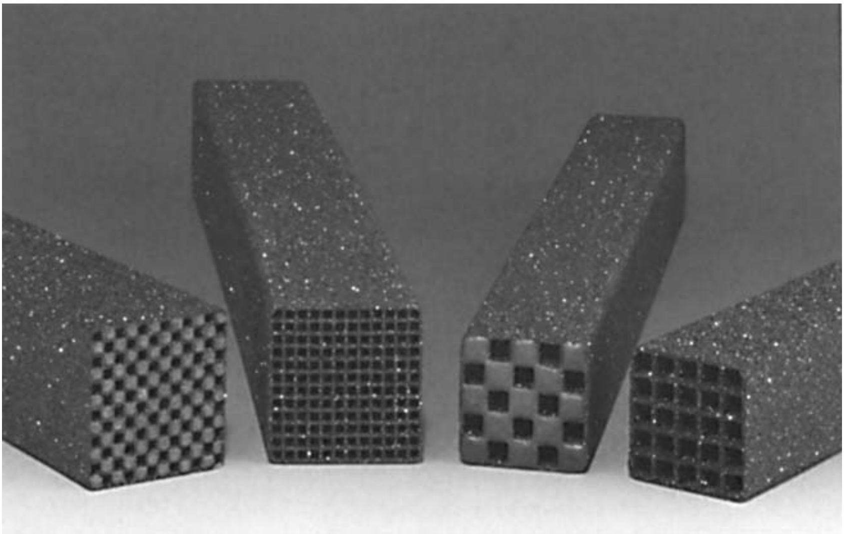


Figure 5.7 Diesel exhaust filter elements

Air filter sizing

The size of air filter required can simply be based on the air consumption requirement of the engine, which theoretically is given as twice the swept volume of one cylinder, multiplied by engine speed, multiplied by the number of intake strokes occurring together (i.e. the number of cylinders). For practical purposes, this can be simplified to the following:

$$\text{filter capacity, m}^3\text{/min} = \text{l.d}^2\text{. N/500k}$$

where bore (d) and stroke (l) dimensions are in centimetres, N is in RPM, and k is a conversion constant, listed in Table 5.2 for different types of engine.

Cabin ventilation filters

The need for proper ventilation of vehicle cabins, whether an agricultural tractor, a private car or a passenger airplane, has been recognized only comparatively recently. This means that air intake (or recirculation) filters are not only required, but also must be able to remove airborne dust, pollen and microbes very efficiently.

Vehicle cabin ventilation filters are designed to supply fresh filtered air into the passenger compartment through the automotive heating and air conditioning, or interior air recirculation systems. These filters can be more than 90% efficient and, where electrically charge fibres made from 100% polypropylene are used as the filter medium, so

Table 5.2 Air filter sizing constants

Type of engine or compressor		k
1	Cylinder four-stroke or two-stroke	18,000
2	Cylinder four-stroke or two-stroke	18,000
3	Cylinder four-stroke or two-stroke	18,000
4	Cylinder four-stroke or two-stroke	18,000
3	Cylinder two-stroke	12,000
5	Cylinder four-stroke	12,000
6	Cylinder four-stroke	12,000
4	Cylinder two-stroke	9000
7	Cylinder four-stroke	9000
8	Cylinder four-stroke	9000
12	Cylinder four-stroke	6000
16	Cylinder four-stroke	4500
1	Cylinder single-acting single-stage compressor	18,000
2	Cylinder single-acting single-stage compressor	18,000
3	Cylinder single-acting single-stage compressor	12,000
4	Cylinder single-acting single-stage compressor	9000
6	Cylinder single-acting single-stage compressor	6000
1	Cylinder double-acting single-stage compressor	18,000
2	Cylinder double-acting single-stage compressor	9000
3	Cylinder double-acting single-stage compressor	6000
2	Cylinder single-acting two-stage compressor	18,000
4	Cylinder single-acting single-stage compressor	18,000
6	Cylinder single-acting single-stage compressor	12,000
2	Cylinder double-acting single-stage compressor	18,000
4	Cylinder double-acting single-stage compressor	9000
6	Cylinder double-acting single-stage compressor	6000

dust, pollen and bacteria are trapped, mechanically as in conventional filters and electrostatically to capture the charged particles. Some typical filters used for this purpose are shown in Figure 5.8, and the topic is explored more thoroughly in Section 6.

Oil filters

The function of the oil filter is to deal with contaminants that are contained in the engine's lubricating oil system, and prevent them from reaching sensitive engine parts, without restricting normal oil flow to the various points requiring lubricating. The oil pump is mounted within the engine oil sump, with the filter connected to give either full-flow filtration or bypass treatment. The former passes all the oil output from the pump through the filter, which is normal in modern practice, although the bypass system is still used on some designs.

Internal sources of contamination include wear products from the rubbing surfaces of the engine, blow-by gases leaking past the piston rings and degradation of the oil

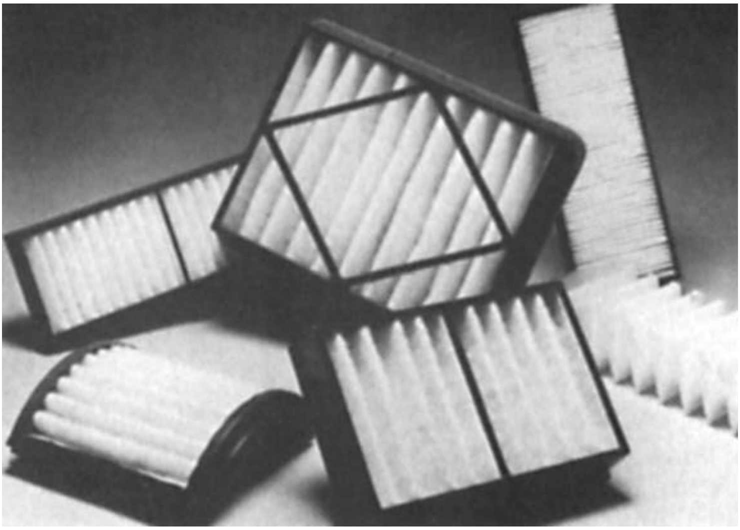


Figure 5.8 Cabin air filters

itself. Modern crankcase lubricants are capable of dispersing many of the contaminants that once caused sludge and varnish deposits to occur, as well as containing additives that greatly extend oil life (that is, prevent oxidation, chemical breakdown or other forms of degradation). Synthetic lubricants are also meeting the demands of high performance engines, and the API standards in resisting the formation and build-up of the black sludge that can cause engine failure by the blockage of oil flow.

Conventional oils are based on blends of mineral oils that are produced from natural crude oil by well established refining processes. Multigrade oils that are light, with low viscosity, provide good flow properties, but can be unstable at high temperatures. Heavy, high-viscosity multigrade oils generally do not have the flow properties necessary to maximize protection over a wide range of temperatures.

In many cases, oil manufacturers add carefully selected chemical additives to the base blend, so as to control flow characteristics or boost protective properties and other aspects of the oil's behaviour. In addition, at the initial refining stage, a further process is often introduced to remove sulphur and aromatic compounds from the crude oil, thereby modifying the molecular structure of the oils from which the lubricant is selected. This oil can generally provide better resistance to the oxidizing effects of air and reactive combustion gases in an engine even under sustained high speed and high stress, as well as improved thermal stability and better resistance to wear.

Synthetic and semi-synthetic oils have been developed from blends of chemicals that are more man-made than natural. They are considered to be high performance products with the ability to meet performance standards and have controllable, stable flow characteristics. They attempt to achieve a careful balance between the desired flow properties and a high level of protection without compromising performance at different temperatures.

Wear products are normally highly abrasive, and are produced mainly during the first ten to twenty hours of the engine's life. Satisfactory protection is provided by both an oil change after a nominal running-in period, as specified by the manufacturer, and fitting a system filter. In some cases, running-in may be completed on a dynamometer rig.

Blow-by gases are comprised of exhaust gases and unburnt fuel mixtures leaking into the crankcase with each complete cycle of the pistons. They are, in the main, removed through the crankcase breather, but can react with an oil which is not in good condition, or on other contaminants. Piston rings can never provide a complete gas seal, so blow-by gases are always present in the crankcase. It is also significant that the presence of foreign matter in the piston ring areas can seriously decrease their efficiency, resulting not only in loss of engine performance, but also giving a higher proportion of blow-by gases below the pistons.

Additional protection for the oil circuit is provided at the oil pump intake, usually in the form of a simple strainer. This will prevent larger particles from entering the pump and the recirculatory system. Properly located and with a suitable design of sump, this will also prevent the pump from picking up water that may have contaminated the oil. This water will normally, but not necessarily, separate out at the bottom of the sump. In the presence of other contaminants it may, of course, form an emulsion with the oil.

Because new oil is now commonly dispensed from sealed cans and enters the engine with the manufacturer's purity, filtering of top-up or filling oil is not considered necessary, although obvious precautions such as wiping clean the neck of the filter, and not pouring new oil from a dirty container or through a dirty funnel, must be observed. Other sources of external contamination are dust entering the dipstick hole when the dipstick is removed and replaced, or through the crankcase breather. When the engine is operated in dust-laden atmospheres, the open end of the breather may need to be fitted with its own filter. In other cases, sufficient protection is afforded by terminating the open end of the breather inside the air intake filter.

Full-flow oil filtration

A typical full-flow system is shown in Figure 5.9, where the filter is in line between the pump and bearings, or other points to which the oil is distributed. The main limitation with this arrangement is that the oil pressure in the bearings depends partially on the flow restriction caused by the filter, plus the fact that the filter must, of course, be large enough to handle the volume of oil flow involved. This may be as high as 25 l/min on larger automobile engines.

Pressure drop through the filter will be affected by the condition of the filter, and also the viscosity of the oil. Thus, with cold oil, pressure drop may be excessive, and, as a safeguard against this, such filters usually incorporate a valve that opens to bypass the filter element. This is normally set to open when the pressure drop across the element reaches a figure of about 1 bar. The bypass valve closes immediately the oil has warmed up and its viscosity falls sufficiently to reduce the pressure drop

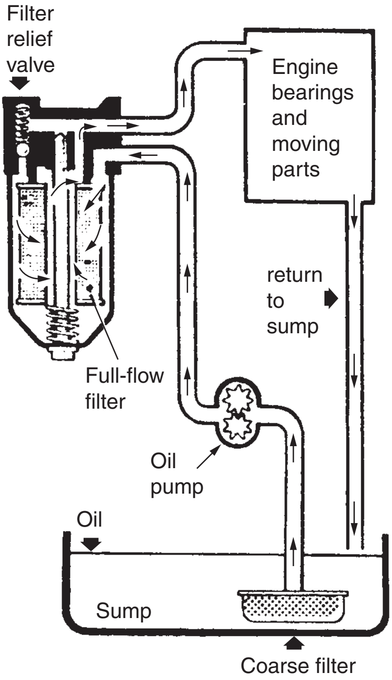


Figure 5.9 Full-flow oil system

across the filter to below 1 bar. If the excessive pressure drop is due to another cause, such as a clogged element, the bypass valve will remain open as long as that cause remains. In such circumstances, the filter remains out of circuit.

A further refinement that may be incorporated in full-flow filters is an anti-drainback valve. The sole purpose of this valve is to prevent oil draining back through the filter into the oil pump, and therefore the sump, when the engine is stopped, thus keeping the filter full of oil. On restarting, oil is thereby circulated immediately from the filter to the bearings. If the filter could drain when the engine stopped, no oil would flow to the bearings until the engine had run for a sufficient time after restarting for the oil pump to fill the filter first.

An alternative solution to the drainback problem is to mount the filter at such a position that, with the engine stopped, it cannot drain back and empty itself through the pump. Since, however, the filter is normally mounted externally and higher than the sump, for ease of replacement of the element or cartridge, the attitude of the filter alone may not be sufficient to guard against siphon draining, in which case an anti-drainback valve can be used to advantage.

Almost all full-flow oil filters are of the surface medium type, since this provides a minimum restriction to oil flow. The filter comprises two parts, a filter housing and a filter element or cartridge. In most designs, the housing and cartridge are combined in a single unit, which can be unscrewed and replaced with a new unit when a filter change is called for. This form of filter is now widely used by almost all engine manufacturers.

Various materials are used for disposable oil filter elements: paper, felt, bulk fibre, wound yarn and spun bonds. The impregnated paper element, of pleated form, is still one of the most popular types, as this can provide a cut-off of the required order and also has the necessary strength to withstand the differential pressures that may be involved. This element is arranged annularly in a circular can with perforated inner and outer tubes to produce the cartridge. Similar construction applies in the case of a replaceable unit where the cartridge is permanently fixed inside the outer casing.

Although many of the newer types of synthetic materials are being used in oil filter elements, felt elements are still used for large capacity diesel engine oil filters because of their property of filtering in depth with large dirt-holding capacity and low pressure drop. Synthetic fibre felt is superior to natural fibre felt in density and uniformity, resistance to engine acids and complete resistance to water. It is also a stronger material. All pleated felt elements are normally supported either by special spacers, or wire mesh, to withstand the operating pressure.

Bypass filtration

Four cycle diesel engines generally need full-flow and bypass filters together. Bypass filtration helps to reduce rod and main bearings wear and piston ring wear. A bypass system is shown in Figure 5.10. Here, the oil pump feeds the main gallery

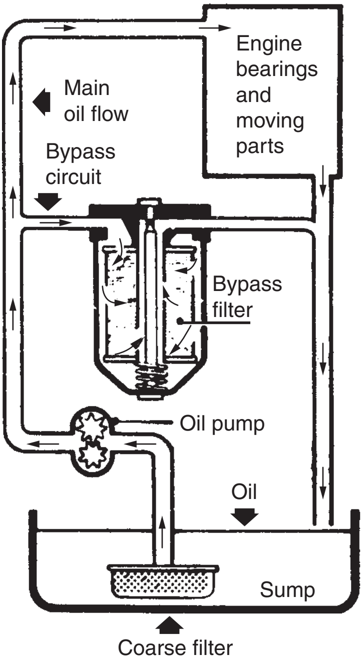


Figure 5.10 Bypass oil system

directly, but this feed line is tapped and taken to the filter with a return line from the filter to the sump. Oil is fed at the same pressure to the bearings and filter, but the actual quantity reaching the filter is controlled by a restrictor usually incorporated in the filter itself. This ensures that the bearings receive the main oil supply, with only a proportion of the oil delivered by the pump passing through the filter. This part flow filter requires no relief valve as it automatically isolates itself in the event of becoming clogged. Nor does it need an anti-drainback valve, as initial flow from the pump to the bearings is not dependent on the filter's being filled with oil. In some cases, though, an anti-drainback valve may be incorporated in the filter, to ensure faster initial circulation to the bearings.

In the case of bypass filter systems it is generally recommended that the rate of flow through the filter should be at least 1/10 of the flow rate of the engine, and that the quantity of oil treated by the bypass filter per hour should be at least five times that of the total oil volume in the circulating system. The bypass system has the advantage that the same size of filter will have a higher efficiency than a full-flow filter, since the flow rate is lower. However, the protection offered is incomplete and the oil has to circulate a number of times before there is the probability that the total volume has passed through the filter. This is still a probability rather than a certainty, and particles can readily bypass the filter line and be fed directly to the bearings. It offers a solution where volume flow is high and would need a large sized full-flow filter, or high flow rates with lowered efficiency through a small full-flow filter. Practical evidence favours the full-flow filter as the logical choice for modern automobile engines, of all types and sizes.

Centrifugal oil filters are also employed as bypass filters, particularly on larger and stationary engines. Their performance is generally superior to paper or felt element filters, particularly in regard to their filtering capacity at high levels of contamination. They are appreciably more expensive than simple filters and are not normally employed for general vehicle applications. Also they are not regarded as suitable for full-flow filtration.

Oil filter rating

The degree of filtration required for satisfactorily protection has tended to become more stringent with modern engine designs, and production techniques, which yield closer tolerances. Whereas a filter cut-off of 30 μm or higher was considered adequate a decade or two ago, the present standard is to provide filtration of particle sizes of 5–20 μm with high efficiency (over 99%).

Oil filter size

The size of oil filter required is determined by the flow capacity and acceptable pressure drop. Increasing the flow rate through a particular size of filter will increase the pressure drop. A suitable size of filter is normally established on obtaining the necessary flow rate with a pressure drop of the order of 0.2–0.3 bar at the usual working viscosity of the liquid. If necessary, two or three more filter units can be mounted in separate housings on a common head to operate in parallel, rather than resorting to a single large filter of the same capacity. Maximum working pressures for lubricating oil filters are usually of the order of 7 bar. This figure may be approached when the oil is very cold, but the normal working pressure is usually around 3.5–4 bar.

Oil filter life

The life of a modern lubricating oil filter element is the order of 500–1000 hours, although this will depend on the working conditions (as in Table 5.3). It is impossible to give specific figures, since the life will depend on engine design, quality and type of lubricating oil, and operating conditions, as well as frequency of oil changes and the actual time elapsed between oil changes. Engine manufacturers give specific recommendations that are commonly held to be conservative or 'safe'. Under certain operating conditions, it may be highly desirable to effect a filter change at much closer intervals. Equally, if a filter change is specified in terms of engine hours or mileage only, the oil filter should be changed at least once a year regardless of whether the recommended hours or miles have been achieved. This is particularly necessary in the case of marine engines derived from automobile engines where less than 500 hours engine running time is commonplace during a single year.

Table 5.3 Oil filter element life

Application	Normal use	Arduous conditions	Poor operating conditions and unfavourable ambient surroundings
Automobile engines	500–1000 h or 10,000 miles	Up to 500 h or 5000 miles	100–250 h
Marine engines	1000 h	500 h	500 h
Large stationary engines	1000 h	500 h	–
Turbines, etc.	2000 h upwards	Up to 2000 h	–
Portable power units	1000 h	500 h	200–500 h

5C. OIL–WATER SEPARATORS

Numerous processes and service operations generate oily wastewater, the disposal of which is usually subject to legislatory and environmental requirements. Tankering to some other place is the simple answer, whereby a contractor is paid to collect the wastewater and dispose of it; but this can prove to be the least cost effective disposal method, and in any case it only transfers the basic problem from one site to another. On-site treatments are therefore almost always to be preferred, but need to be matched to the kind and proportion of oil contaminant, its condition (i.e. whether free or emulsified), and to the presence of other contaminants.

Incineration is a possible (although never a popular) on-site treatment. The achievement of successful incineration may demand the use of special incinerating equipment with gas or fuel oil present in the waste. Emulsified wastes, although containing a significant proportion of water, are often more readily incinerated than heavier oily wastewater.

Settlement under gravity is a direct low cost treatment, but involves the use of bulky separator tanks. Also such tanks need to have correct proportions for optimum performance, for example, a minimum depth-to-width ratio to ensure that the linear liquid velocity through the separator is not high enough to cause remixing of the oil and water. Hence, gravity separators are essentially specialized designs. A gravity separator in the form of a horizontal cylinder is shown in Figure 5.11.

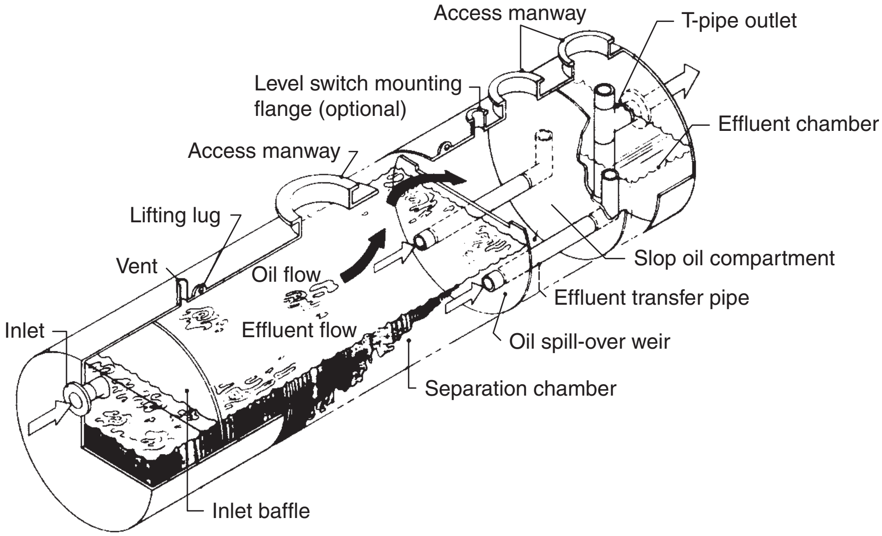


Figure 5.11 Cylindrical gravity oil–water separator

The American Petroleum Institute recommends various minimal horizontal and vertical cross-section areas and depth-to-width ratios. These minima are based on the formula version of Stokes's law, which relates the rate of rise of an oil droplet through a tank of water to (among other things): the difference between the liquid densities and the square of the droplet diameter.

It is important to know the oil globule size because the rate of rise of the globule increases as the square of the diameter. Considering two applications, when in which all factors are the same except for oil globule size, when the following will hold true: that a 150 μm oil droplet will rise nine times faster than a 50 μm one ($150/50 = 3$, and $3^2 = 9$).

The greater the differential between the specific gravity of oil and the continuous phase, water, the faster the rate of rise. Thus, the specific gravity of number 2 fuel oil is 0.85, while that of number 6 fuel oil is 0.95. The differentials from fresh water (specific gravity 1.00) are 0.15 and 0.05 respectively. As a result, the rate of rise of the number 2 fuel oil will be three times that of the number 6, assuming that both are in a free oil condition.

A gravity separator to API recommendations for treating 55 l/s of oil needs to be 20 m long, 3.35 m wide and 1.8 m deep. This can provide fairly rapid separation of oil from water, to a point where the wastewater is suitable for discharge.

In smaller gravity separators, or separation columns, the time taken for separation may be as high as two or three days. This will allow the majority of the sludge to settle. Four distinct layers are formed, consisting of an uppermost layer of oil, followed by light sludge, water and bottom sediment. A concentrating funnel at the bottom of the tank or column facilitates sludge removal, and waste oil can be drawn off from the upper layer by means of a float take-off and treated further, if necessary, for example by being reclaimed.

Gravity separation may be speeded up by increasing the temperature of the influent, although this further complicates the design, and calls for particular attention to avoid heat losses. By the same premise, the performance of an unheated gravity separator will be subject to seasonal variations, being most effective at high ambient temperatures and least effective in winter conditions.

Coalescing separators

When a coalescing medium is installed in the separating chamber, this provides a surface on which oil globules can combine or agglomerate. The closer the surfaces of the medium, the shorter the distance through which the oil has to rise and so the quicker it is removed from suspension. The expanding globules work their way up through the coalescing medium, eventually breaking free from it to rise through the continuous phase. The faster separation means less retention time is required than for straight gravity separation. The use of a coalescing medium enables the removal of smaller oil particles: an API-type separator is designed to remove 150 µm oil globules (free oil) whereas a coalescing separator, of the proper design, can remove oil globules as small as 20 µm. The size of separating chamber is substantially reduced compared with an API separator.

The coalescing medium used needs to have oleophilic properties for optimum oil retention. At the same time, such a property usually means that the medium is water repellent. Plastic materials such as polypropylene and PTFE have proved to have excellent coalescing properties, and are used in the form of plates or tubes in the kind of arrangement shown in Figures 5.12 and 5.13. The tube type is claimed to have a superior performance. This kind of coalescing oil–water separator is designed to remove oils, fuels and hydraulic fluids from water. The tank is constructed in fibreglass, making it light weight and portable for use in a wide range of applications, including workshops, ship bilge processing, chemical plants, and oil fields and refineries.

The inclined plate (or tube) separator is widely used throughout industry, and is often combined with fine solids removal. The solids settle downwards between the plates, to be removed intermittently from the water tank at the base.

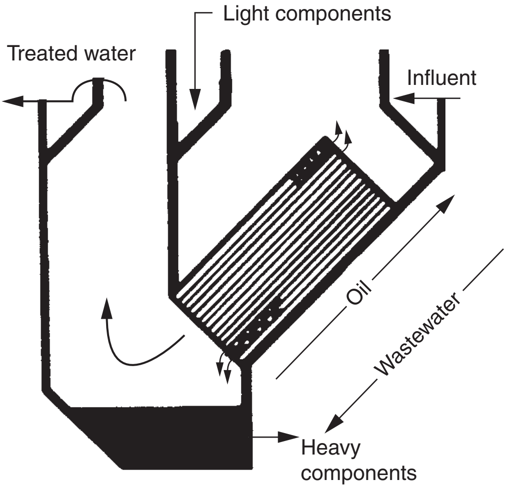


Figure 5.12 Parallel plate separator schematic

Figure 5.13 Parallel plate coalescing separator

Self-cleaning oil and water separators are typically single-stage devices designed to separate and remove non-soluble oils, solids and entrained air from oily water, in marine duties. The system incorporates tilted plate separation and a stationary polishing pack in a single stage. Other applications include coolant separation, tank farming and repair shops.

Emulsified oily wastes can present particular problems in handling, such as those originally intended to behave as emulsions (e.g. machine tool coolants), because of the stable nature of the emulsions involved. Two basic methods used on emulsified wastes are:

- chemical treatment to neutralize the effect of the emulsifiers, allowing the oil to separate out, and

- heating to near boiling point to separate the oil and water phases, together with chemical dosing if necessary.

With the first of these, chemical splitting, final treatment is then in a separator. With the second, thermal splitting, complete process equipment is normally involved, incorporating heat exchangers associated with evaporators or centrifuges.

Hydrocyclones

Hydrocyclones are capable of separating any immiscible, insoluble liquid–liquid mixture. The differential pressure they require in order to operate can be as little as 2 bar. The operating principle of the hydrocyclone is shown in Figure 5.14. It has a cylindrical shape, usually mounted vertically, with a larger diameter upper cylinder tapering down to a narrow cylindrical section, which is the heavy phase outlet. Oily liquid enters the unit through a tangential inlet at its top. The tangential feed causes the liquid to form a vortex, with the influent liquid forced to the periphery of the shell. The flow is directed down the shell, without disrupting the reverse-flowing separated oil in the core. As the flow follows its helical path along the wall its self-induced centrifugal force causes the denser water to separate to the wall, and the oil to move inwards towards the centre. In the conical section, the flow is accelerated to give the higher centrifugal force necessary to complete the separation of the oil,

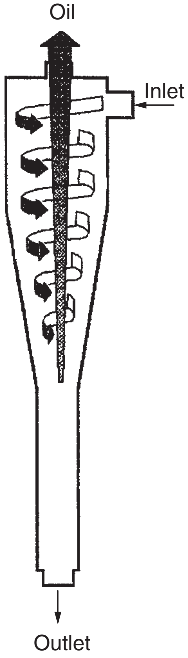


Figure 5.14 Hydrocyclone operating principle

which turns through 180° at the throat of the tapered section, and returns up the centre, picking up other separated oil as it goes, to reach the vortex finder at the top and so be discharged. The water, now free of oil, continues on down and out of the lower discharge port.

The application of a back pressure to the water outlet ensures that the oil is drawn into the low pressure core, and flows back up the hydrocyclone to be removed at the upstream outlet, at a rate controlled by the back pressure.

Hydrocyclones can offer an efficient and cost-effective means for separating large or small quantities of liquid–liquid effluent mixtures, and are worth considering as an alternative to settling tanks, coalescence separators, dissolved air flotation and centrifuges for oily water treatment.

Oil removal from separators

Most separators have an internal collection area or reservoir for accumulating skimmed oil. The simplest method of transferring separated, floating oil to the internal reservoir is to provide an adjustable overweir. This type of skimming device can be adjusted to skim a predetermined level off the top surface as the flow moves through the unit. Oil flows over the weir and into the internal reservoir for removal.

If the separator has an oil overweir with a collection sump (and a relatively constant dynamic flow), a skimmer is not essential. A skimmer may be used to advantage in certain applications to overcome the inflexibility of an overweir and may be of an adjustable level or automatic (floating) type. The latter can be capable of removing virtually water-free oil, with a possible recovery value.

Other oil removal methods

Other oil–water separation methods used include chemical treatment, to provide coagulation and/or flocculation, followed by sedimentation or flotation, air flotation alone, acid cracking, thermal splitting and filtration. In the case of flocculation, gravity separation can generally be best accomplished with clarification. Clarifiers usually have an advantage over air flotation if the floc settles quickly. Properly sized, they are more efficient in removing some flocs; also, power requirements are less and they are easier to maintain. A clarifier may not be suitable if the floc has a near-neutral buoyancy, and thus a very long settling time. In other words, an extremely long detention time would require too large a clarifier. A better alternative is then air flotation.

Flotation

There are two common types of air flotation: dissolved and dispersed. Dissolved air flotation (DAF) involves the use of pressurized water, in which air has been dissolved. This water is then pumped into the bottom of the tank containing the wastewater. The release of pressure allows the air to separate from the water generating billions of tiny bubbles, which lift the flocs to the surface.

In dispersed air flotation the air is not dissolved in water, but is forced into the base of the tank through sparge pipes perforated with tiny holes. The bubbles are larger and fewer in number than with DAF. The typical bubble size is 80 µm for dissolved air flotation and around 1 mm for dispersed flotation.

Typical air flotation units are made in single and multi-cell configurations. Stickier scum and sludge can usually be obtained from flotation equipment rather than a clarifier, but such units are commonly used in combination with a clarifier.

Filtration

Filtration is more normally used as a post-treatment process, further to improve the water quality. However, oil–water separators are also designed on a filtration basis. When two non-miscible liquids of different densities flow by gravity through a porous medium, they will have different penetrability rates. In such a filter, the oil–water mixture first enters a sedimentation tank, where heavier particles settle out. The oil–water mixture then enters an inlet basket and flows into the porous medium, where the oil separates from the water. The water flows on down through a screen at the bottom, then up and over a water weir, which creates the water table supporting the oil longer. The oil travels horizontally on top of the water into the oil trap and then over an adjustable oil weir, which is set at a position slightly above the maximum water level.

Ultrafiltration

A more straightforward, and increasingly important process, which can be used for oil–water mixture separation, and especially for breaking oil–water emulsions, is ultrafiltration, using suitably designed membrane filters. These differ from conventional filters in that the flow is usually tangential to the filter medium rather than at right angles to its surface (cross-flow filtration).

Ultrafiltration is a membrane separation process, used for the concentration and purification of macromolecular dissolved solids and very fine suspended solids (colloids), in which the solution is caused to flow under pressure across the membrane surface. Solubles and colloids are rejected at the semi-permeable membrane barrier, while solvents and microsolutes *below* the molecular weight cut-off (MCWO – usually in the range of 1000 to 1,000,000) pass through the membrane as the permeate. The materials retained at the membrane surface are carried on downstream by the flowing process liquid as retentate (or concentrate). The pro-cess is directly comparable with reverse osmosis, but because of the looser, more open membranes used for ultrafiltration, operation pressures of only 0.6–6 bar are needed (as against 20 to 100 bar for reverse osmosis).

In a typical unit, illustrated schematically in Figure 5.15, waste oil–water feed is introduced into an array of membrane modules (four are shown in the figure). Water and low molecular weight solutes (such as salts and some surfactants) pass through the membrane and are removed as permeate. Emulsified oil and any suspended solids are rejected by the membrane and are removed as concentrate.

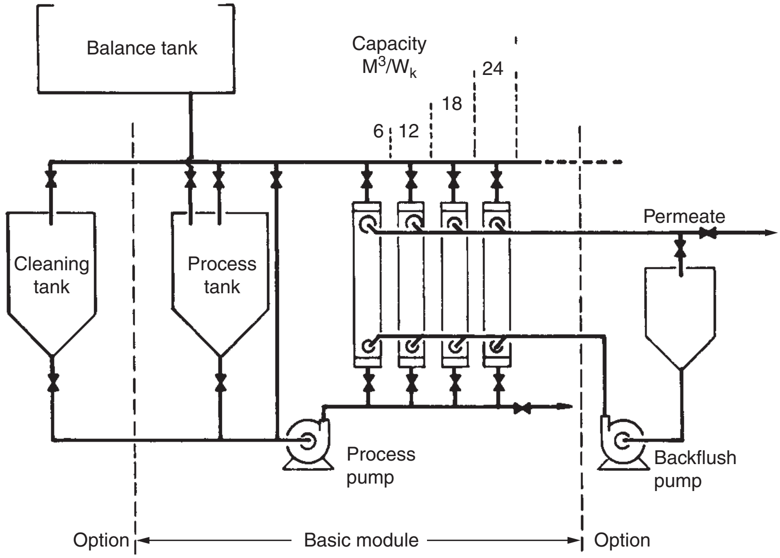


Figure 5.15 Waste oil ultrafiltration

Ultrafiltration is perfectly familiar in the industrial world and is used widely in numerous processes. The actual separation is carried out by the semi-permeable membrane itself, but the performance of the units, and especially the ultrafiltration flow rate and its regularity, depend on a number of factors: the intrinsic properties of the membrane used, the operating conditions, and the characteristics of the modules in which the membranes operate. It is for this reason that the choice of ultrafiltration module technology is specially important for industrial applications, where economical considerations are at least of the same importance as technical ones.

In fact, in the process of ultrafiltration, the phenomenon that dominates, and in practice determines, unit performance is that of over-concentration at the membrane surface, which creates a limiting layer (also referred to as a concentration polarization layer), which may be accompanied by the formation of a gel layer in the case of colloidal suspensions or solutions. A reduction of the degree of this phenomenon can only be obtained by increasing the sheer or turbulence effect in the liquid flow across the membrane. This can be achieved by increasing the flow rate, which leads to circulation flow rates that are higher where the module's dead volume per unit surface area is larger, thus reducing the thickness of the film. It can also be achieved by reducing the diameter of the membrane tube, or of the size of any other flow channel. Depending on the technique selected, this solution causes an increase in the pressure drop, especially when the product treated has a high viscosity.

A major alternative means of increasing the turbulence in the zone adjacent to the membrane surface is by use of moving surfaces close to the membrane – either a moving non-membrane close to the membrane, or a moving membrane close to a stationary surface. The movement can be rotational or vibratory.

A typical ultrafiltration system is made up by assembling membrane holding plates and separating plates, which are pressed together between the plates of a frame press, which also acts as a support for the assembly. On the fixed plate of the frame press there are the inlet connections, and on the mobile plate there are the outlet connections for the liquid being treated. The membrane holding plates have on each face transverse grooves into which the membrane is placed, and held by two pairs of sealing rings, which also act as ports for the liquid to be treated. The grooves play a dual role, draining the ultrafiltrate towards the collecting channels situated on either side of the plate (so that it can be evacuated to the outside via two nipples located on each side at the bottom of the plates), and increasing the turbulence in the liquid being treated, which has the effect of improving performance. The number of holding plates in each sub-assembly, and the number of sub-assemblies for each module, are determined by the nature of the products to be treated, the required working conditions and the total surface area desired.

The average ultrafiltration flow rate, its evolution with time and the cleaning frequency vary depending on the product being treated, the operating parameters (in which temperature plays an important role) and the degree of concentration required.

5D. OIL CLEANING

Oil of any kind is no longer a cheap commodity (having recently reached a record high price), so cleaning and reclaiming oil from industrial systems, where it has become contaminated, is an important and necessary process, as well as a profitable environmental investment. It usually becomes very cost-effective to install an oil treatment plant where annual oil consumption exceeds about 1000 litres, or in systems with a reservoir capacity of 500 litres or more. The light equipment, previously used for off-shore and marine systems, is now replacing heavier and bulkier equipment for this purpose.

The actual treatment required varies widely from plant to plant, depending upon the amount and nature of the impurities present. Several stages of pretreatment may be necessary, such as screening and/or gravity sedimentation in a settling tank to remove coarse impurities, before final cleaning.

Even distillate fuels are not contaminant free. They can often contain water, and trace metals such as sodium, vanadium and lead, which may cause serious corrosion problems. Operators using distillates often ignore the fuel quality as a possible source of a problem. The contamination comes from storage and delivery methods, more often than from refining.

There are a number of standard methods in use to clean distillates. These include:

- combined filtration and coalescing
- centrifugal separation
- water washing followed by centrifugation

- water washing followed by electrostatic precipitation, and
- settling out tanks.

On balance, centrifugal separation with or without water washing is considered to be an effective method.

Filtration

For oil cleaning, filters have the advantage of being straightforward, low cost units, with the ability to remove all suspended solids down to a specified size. Figure 5.16 shows a multiple element filter consisting of four or six elements in one housing, all working at the same time. The flow of oil carries the particles of contaminant into the depths of the filter medium, without flow restriction from surface loading. The hydraulic pressure of the oil compresses the layers of medium against a seal and toward the centre of the element, creating a constant pressure to avoid channelling. This compression, along with the pressure against the filtering surface of the element, causes the elements to become compacted, trapping contaminants down to 1 μm. Oil flow is through the leaves of the element and into the oil return tube of the filter housing.

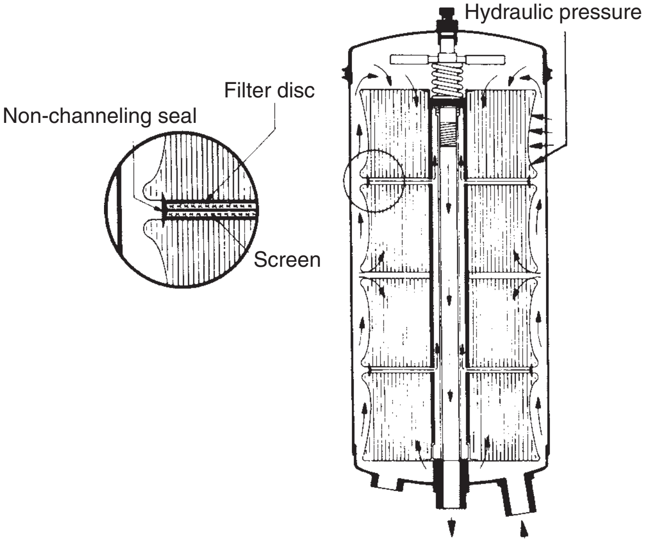


Figure 5.16 Multi-element oil cleaning filter

Filters of this type can be incorporated in recycling and coolant reclamation systems ranging from 220 litres to 13,500 litres capacity. The types of fluids that may be reclaimed include water-based coolants, synthetic hydraulic fluids, water/glycol mixtures, hydraulic oils, automatic transmission fluids, ester-based fluids, cutting oils, lubricating oils, drawing oils, quench oils and gearbox oils.

Oil cleaning units incorporating filters can remove ultra-fine contaminants and, to a certain extent, water. They do also have a limited ability to handle high sludge concentrations or viscous fluids. The oil cleaning system shown in Figure 5.17 incorporates a five housing element filter system, and is used for handling most fluids from automotive crankcase oils to some of the more exotic industrial fluids.

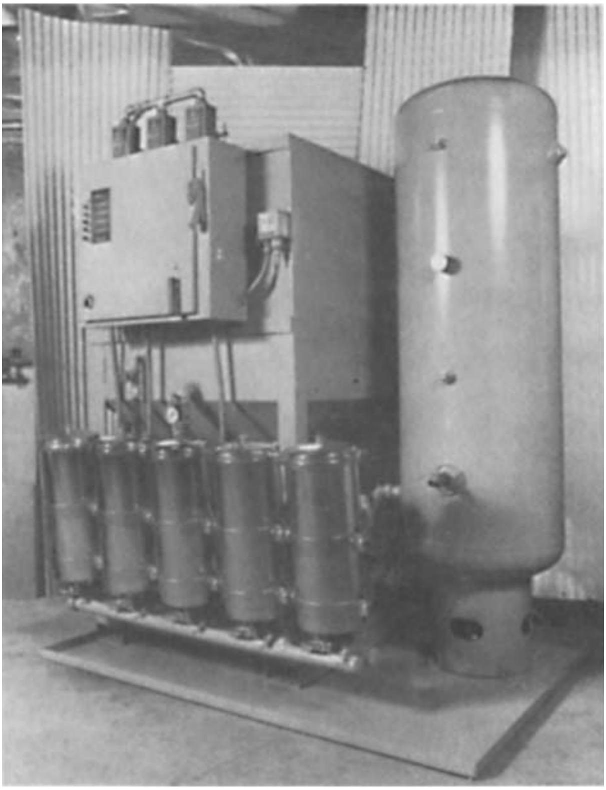


Figure 5.17 Oil cleaning system

Centrifugal oil cleaning

Although they do not work by filtration, centrifuges are an important means of oil processing, and so are discussed in this section. Sedimenting centrifuges have the advantage of being able to handle larger volumes continuously, with high separation and the ability to treat even viscous oils with a sludge content of up to 10% by volume. There are also various types of sedimenting centrifuge available for different duties, which sub-divide into purifiers, clarifiers and concentrators and into solids-retaining and self-cleaning types. These are all disc stack centrifuges, containing a stack of conical sheets (called discs), one above the other with their cone apexes around the central shaft. The discs are mounted close together so that as any mixture flows through the stack its constituents have only a short distance to travel before they become attached to one side or other of each disc. Having become attached, they then move up or down the surfaces of the disc, to its centre or periphery respectively, and so become separated into the two liquid phases (with any solid contaminants thrown out to the wall of the bowl). Such centrifuges are usually built into compact oil cleaning packages, as illustrated in Figure 5.18.

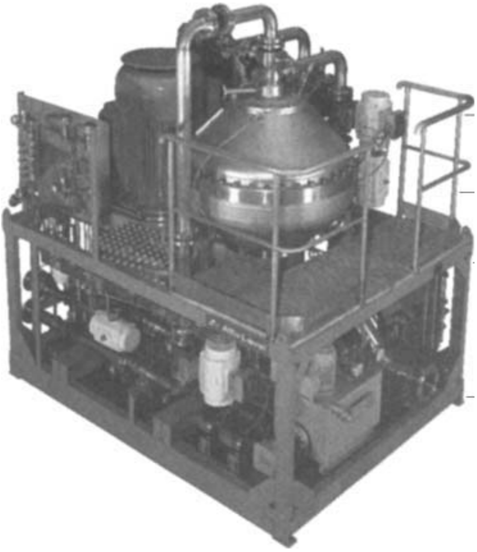
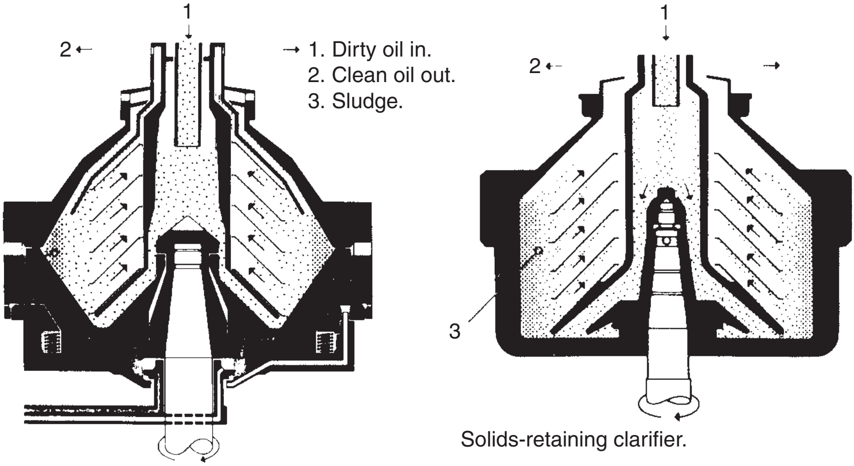


Figure 5.18 Centrifugal oil cleaning package

A centrifugal oil purifier has a bowl designed for the separation of both water and oil as products. The two basic types are shown in Figure 5.19, the right hand image of which shows a bowl that has no means of releasing any accumulated solid whilst running (rather has it to be removed manually from the space next to the wall after the machine has come to a standstill). The left hand image shows a self-cleaning purifier, in which the solids accumulate in the tapered section of the bowl wall, from which they are ejected continuously, through a set of peripheral nozzles, or semi-continuously, by the use of valved nozzles, or a bowl that moves apart to open an annual slit at its periphery.

Operation of these machines begins with the supply of water to the bowl at the start of the run to form a rotation ring with a vertical cylindrical surface inside the edge of the top disc. When the liquid seal has been established in this way, the oil–water



Self-cleaning clarifier.

Solids-retaining clarifier.

Figure 5.19 Centrifugal oil purifiers

mixture is fed to the bowl, and separation commences. The feed rises into the disc stack through aligned holes in the distributor and intermediate discs, whose function is to shorten the free settling path of water droplets and sludge particles. Sludge is deposited on the bowl wall, whilst water passes between the bowl hood and the top disc, to overflow from the neck of the bowl. Clean oil leaves the bowl by the upper outlet.

For optimum separation results, the interface between oil and water in the bowl (known as the e-line) should lie outside the disc stack, but inside the edge of the top disc (to prevent oil from escaping through the water outlet). The position of the e-line is regulated according to oil density by the diameter of the interchangeable gravity disc at the water outlet.

The special portable oil purifier shown in Figure 5.20 incorporates a spinning disc design that can remove 100% of free water, as much as 80% of dissolved water and 100% of free and entrained gases. From the schematic in Figure 5.21 it will be seen that the contaminated oil is drawn into the oil purifier by the chamber vacuum. The oil is fed onto the centre of the spinning disc and is thrown outwards by centrifugal force. At the disc edge, the oil is released as tiny droplets to create an enormous surface area per unit volume of oil. Free and dissolved water, air and solvents are removed by exposing the contaminated oil to a low relative humidity atmosphere, which is obtained by maintaining the process chamber at a vacuum of 610 mm Hg. Dehydrated oil from the vacuum chamber leaves the system through a discharge pump with a 3 μm silt control filter.

Centrifugal clarifiers are intended to clean oil free of suspended solids and so have no separate water outlet holes. Feed is from the outer edge of the disc stack, into the zone of maximum centrifugal force, with sludge separating outwards to the bowl wall.

In centrifugal concentrators, the concentration bowl works in the reverse mode to a purifier. With distribution holes and the interface closer to the axis of rotation, it is designed to remove traces of a lighter liquid (oil) from a denser one (water), while

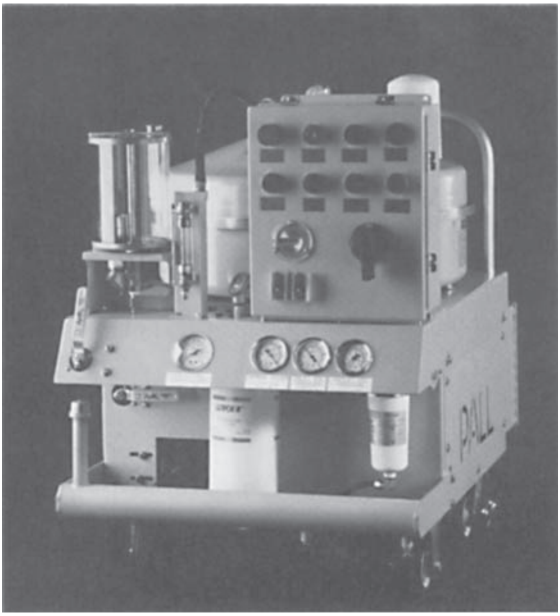


Figure 5.20 Portable oil purifier

removing suspended solids from both liquid phases. Typical concentrator duties include:

- separation of tramp oil from emulsion-type coolants
- reclamation of oil from wastewater, and
- purification of synthetic hydraulic fluids, which are denser than water.

The most common type of disc separator is one having to deal with a mixture of oil and water, with quite a high degree of suspended sludge. Water is separated from the oil with the sludge as a second phase, and if necessary this can be followed by a self-cleaning clarifier to dewater the desludged oil phase. A two-stage centrifuge installation of this type can often dispense with the need for sedimentation tanks, even when dealing with relatively heavily contaminated oils.

A major advantage of the disc centrifuge is the comparative ease with which accumulated solids can be removed. Admittedly, in the case of the solids-retaining centrifuge on the right of Figure 5.19, the centrifuge must be stopped, and the solids removed manually, as in Figure 5.22. For other types, the majority in the field, automatic discharge is arranged, either by the use of open nozzles at the periphery of the bowl, or by the head of sludge in the bowl, which causes valves to open on normally shut nozzles, or opens the bowl completely around the periphery, for just enough time to allow most of the sludge to leave and to retain the liquids in the bowl.

The decanting centrifuge is an effective oil treatment separator, processing mixtures with larger size impurities and higher feed concentrations. In most applications of the decanter it is used to separate a liquid from a solid, a job it does very well,

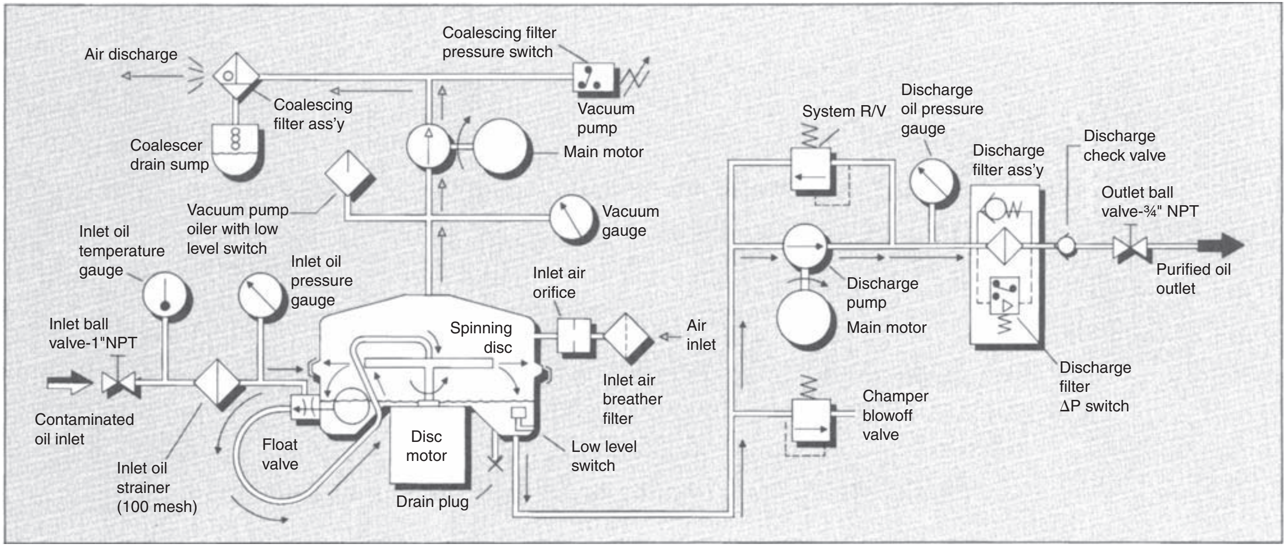
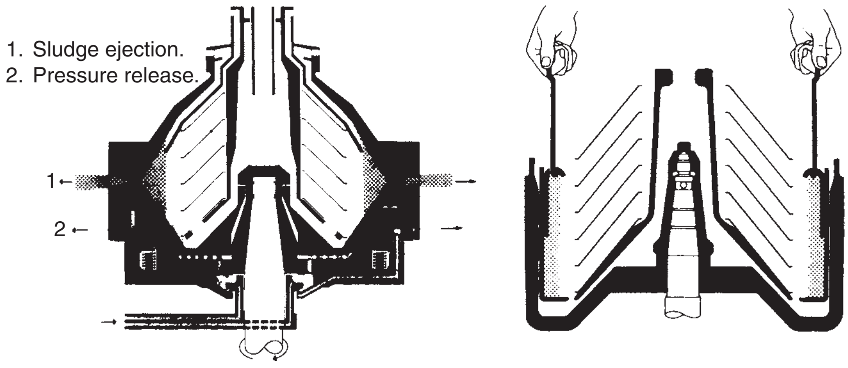


Figure 5.21 Oil purification schematic



Self-cleaning separator: centrifugal unloading.

Solids-retaining separator: manual unloading.

Figure 5.22 Manual removal from disc separator

yielding a solid cake that is quite stiff. In oil cleaning, it is almost always necessary to allow for the presence of water, so the decanter has been redesigned to permit two liquid discharges, one light and one heavy, as well as to discharge any suspended sludge in a fairly dry state. This three-phase decanter is illustrated in Figure 5.23, and it is designed to give high efficiency sedimentation of solids coupled with separation of the two liquid phases.

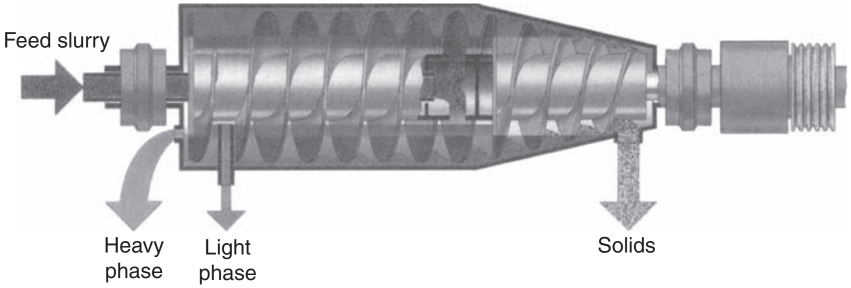


Figure 5.23 Three-phase decanter

Applications for this centrifuge include low temperature fat rendering, reclaiming fat and oil from wastewater, recovering waste lubricating oil, slop oil and sludges from API separators. A process for the recovery of slop oil is shown in the schematic of Figure 5.24, including both a three-phase decanter and a disc separator for polishing the cleaned oil.

If expense is no object (and they are by no means inexpensive) then the sedimenting centrifuges provide a very good, very efficient way of dealing with almost any oilcleaning problem. Table 5.4 summarizes the applications of the various types of centrifugal oil cleaner.

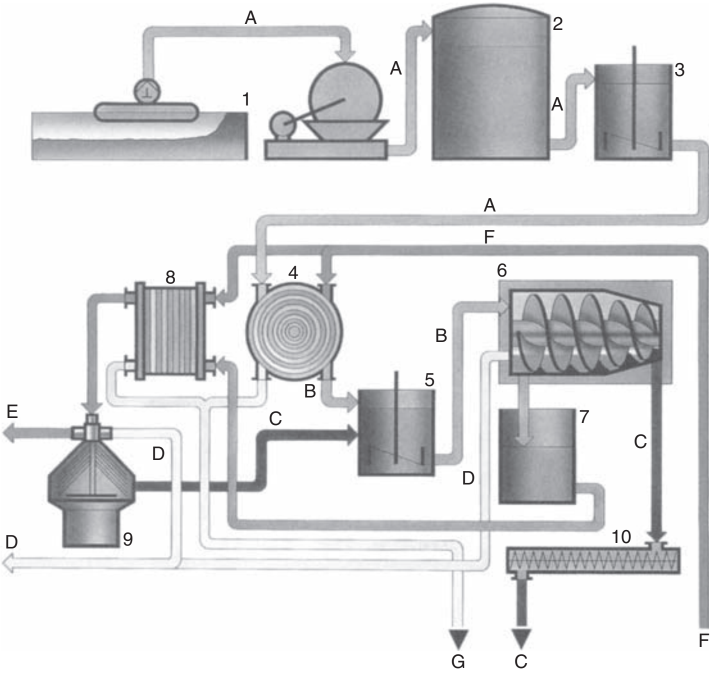


Figure 5.24 Slop oil recovery process (A) Slop oil. (B) Preheated slop oil. (C) Solids. (D) Clean oil. (E) Waster water. (F) Steam. (G) Condensate. (1) Oil lagoon with puming station. (2) Storage tank. (3) Preconditioning tank. (4) Spiral heat exchanger. (5) Preconditioning (mixing) tank for flocculants. (6) Three-phase centrifuge. (7) Storage tank. (8) Plate heat exchanger. (9) Disc separator. (10) Screw conveyor.

Table 5.4 Centrifugal oil cleaner applications

Type	Maximum particle size	Minimum particle size	Maximum feed concentration (%)	Method of sludge unloading	Water removal from oil
Purifier (solids retaining)	500 µm	0.5 µm	10	Manual	As separate phase
Purifier (self cleaning)	500 µm	0.5 µm	10	Intermittent (hydraulic)	As separate phase
Clarifier (solids retaining)	500 µm	0.5 µm	10	Manual	No
Clarifier (self cleaning)	500 µm	0.5 µm	10	Intermittent (hydraulic)	No
Decanter	20 mm	2 µm	40	Continuous (mechanical)	With sludge phase

Coalescing plate separators

Coalescing plate separators, already mentioned in Section 5C, and originally designed for marine bilge water discharge contaminant removal, have gained favour also for use in industrial applications for pollution control and product recovery. Figure 5.25 is a good example of corrugated coalescing plate separators where it uses the plates, not nearly flat and on top of one another, but mounted vertically, side by side, with deep corrugations in the plates.

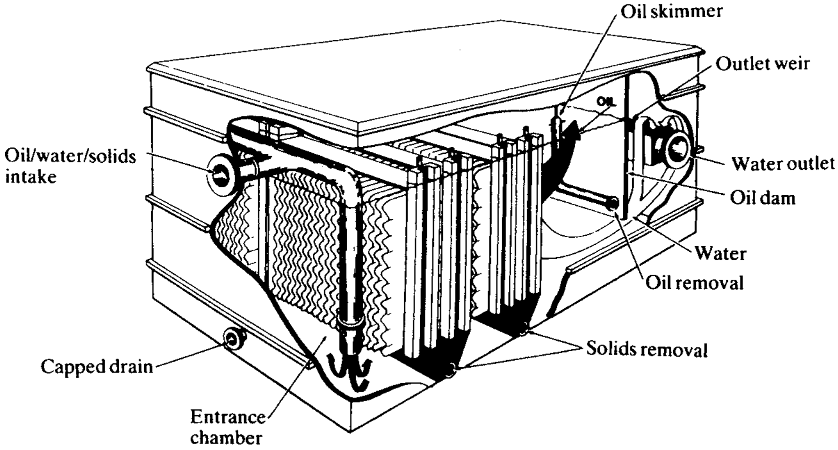


Figure 5.25 Vertical plate separator

In operation, oily water influent is introduced into an inlet chamber by gravity flow or pump. This first chamber is separated from the plate pack section by an inlet weir. Heavy solids settle out here and any 100% oil slugs rise immediately to the surface. The remaining oily water mixture flows on through a stack of closely spaced, corrugated, high density polypropylene plates. Both the smaller oil droplets and any fine solids are progressively separated as the liquid flows through the plate pack. Downstream of the plates, a baffle or oil dam prevents the collected oil from entering the outlet weir. Solids are removed through drains at both inlet and outlet weirs. Manual or automatic oil skimmers remove the oil.

In an alternative arrangement, the corrugated plates are mounted nearly flat, with the corrugations across the path of the liquid flow. The effectively horizontal arrangement of the plates induces a sinusoidal laminar flow pattern in the oil–water mixture. Under laminar flow conditions, buoyancy forces cause oil droplets to rise until they attach themselves to the oil-attractive plates. The droplets then coalesce into thin layers of oil on the undersides of the polypropylene plates. The sinusoidal flow path promotes a high incidence of droplet collision, as the fluid flow constantly changes direction from a downward movement to a vertical path. The coalesced oil rises in the form of large globules through the weep holes in the plates, to the surface of the separator.

According to Stokes's law, with all other matters the same, the rate of rise of an oil drop is directly proportional to the square of the droplet diameter. Thus a 60 μm drop will rise nine times faster than a 20 µm droplet. Because the bigger drops are rising faster than smaller ones, it is likely that, in a mixture where there is a natural distribution of droplet sizes, a larger droplet, say one of 100 µm diameter, rising to the surface at a higher speed, will collide with smaller, slower droplets. These will combine to form even larger droplets, with a still higher rate of rise.

Heating

Heating may be employed where bearing oils are involved, to reduce viscosity and facilitate pumping and subsequent treatment. Heating may also be used to break down emulsified oils. In certain circumstances, particularly where high oil purity is not involved, heating followed by gravity settlement may be sufficient treatment to recondition an oil.

Distillation

Although a long way distant in process terms from filtration, distillation completes the gamut of oil cleaning techniques that are employed. Distillation under vacuum may be used prior to final clarification, to remove light fractions from waste oil, in diluent stripping, dehydration and degasification. Such a process is normally carried out under a medium vacuum (50 torr/mm Hg). It is also particularly suitable for water, air, and solids removal from synthetic oils and hydraulic fluids (such as phosphate ester fluids. Higher vacuum processes, at 1–2 torr, are used for the drying, degassing and filtration of electrical insulating oils.

Low temperature, vacuum distillation oil reclamation systems can handle a variety of fluids, and are designed to remove water and other contaminants that cause oil to become a hazardous waste to the environment, and unable to be re-used. Generally, vacuum distillation should be performed at 60°C or below. The reason for this is that the oxidation rate doubles for every 11°C increase in temperatures above 60°C. Oil reclaimers using distillation incorporate prefilters, final filters and controls in one-piece units.

Insulating oil treatment

Insulating oil plays a vital part in many types of electrical equipment, not only as an insulant but also as a coolant in transformers and as an arc extinguishing medium in circuit breakers. In each case, efficient operation of the equipment depends upon the purity of the insulating oil, which in service can be contaminated by oxidation, condensation and the presence of solids, such as colloidal carbon, formed by arcing in circuit breakers. The electrical and physical properties of the oil may be seriously affected, resulting in reduced operating efficiency or even equipment failure. Frequent replacement of the oil will be too costly, and reconditioning by filtration and vacuum dehydration to remove all contaminants is the economic answer.

The breakdown in the quality of oil is caused in the following ways:

- contamination by dirt and carbon particles
- contamination by water vapour condensation

- gases absorbed from the atmosphere and especially those produced during arc suppression, and
- chemical products caused by oxidation and other chemical action.

New and reconditioned oil-filled electrical equipment will, despite all precautions, contain some moisture and other contaminants. Likewise, oil for filling may be contaminated during storage. Portable insulating oil treatment units pump oil from the equipment through a heater. After the oil is heated to a predetermined temperature, it is filtered using edge filtration. Here, the fluid being filtered passes from the outside to the inside of a pack of circular discs, through minute interstices formed between the discs. After passing out of the filter chamber, the hot oil is sprayed into a vacuum vessel being thereby broken into small droplets. These present the maximum surface area for evaporation of water and gases. The clean treated oil collects at the bottom of the vacuum vessel and is pumped away. The filters are cleaned by backflushing with air on completion of each filtering operation. Figure 5.26 shows a flow diagram of the layout of a vacuum dehydration plant, with its main pieces of equipment, and the flow of oil through the unit. By filling a transformer with hot treated, super-dry oil, and subsequently recirculating it, one causes the cores and windings of the transformer to dry out, which greatly improves its performance.

Oil disposal

Disposing of waste oil can be a costly operation, particularly if it is possible to clean and recover it for re-use. However, most oils eventually become irretrievably contaminated, and the sensible option then is to burn the oil carefully, using the generated energy.

As well as its being trucked to a major incinerator, small waste oil to energy converters are available for converting the oil into clean fuel. Typically, this type of system filters and then blends the waste oil with new fuel at an operator selected ratio of between 0 and 10%. Waste oil is drawn through a 6 μm depth medium filter, then pumped through a 4 μm depth medium filter, removing particulate matter of 4 μm or larger.

Electronically blended ratios of cleaned waste oil to new fuel are automatically controlled to achieve a precise mixture at the required flow rate. Routing the processed waste oil and fuel mixture through a final coalescer assembly removes particulate matter 4 μm or larger, as well as more than 99% of emulsified and free standing water. The process results in an emulsified, precisely blended, clean, water-free fuel that can be used in a diesel engine or other fuel burning device.

5E. HYDRAULIC SYSTEMS

Of all of the utility application of filtration, the filtration of hydraulic systems is probably the most important, because of the critical need to keep hydraulic fluids free of solid contaminants, and because of the very wide application of hydraulic systems themselves: in almost every manufacturing operation, in almost every agricultural and construction machine, and in most commercial vehicles, railway stock, ships and aircraft. Flows in hydraulic systems are not great, and flow channels are

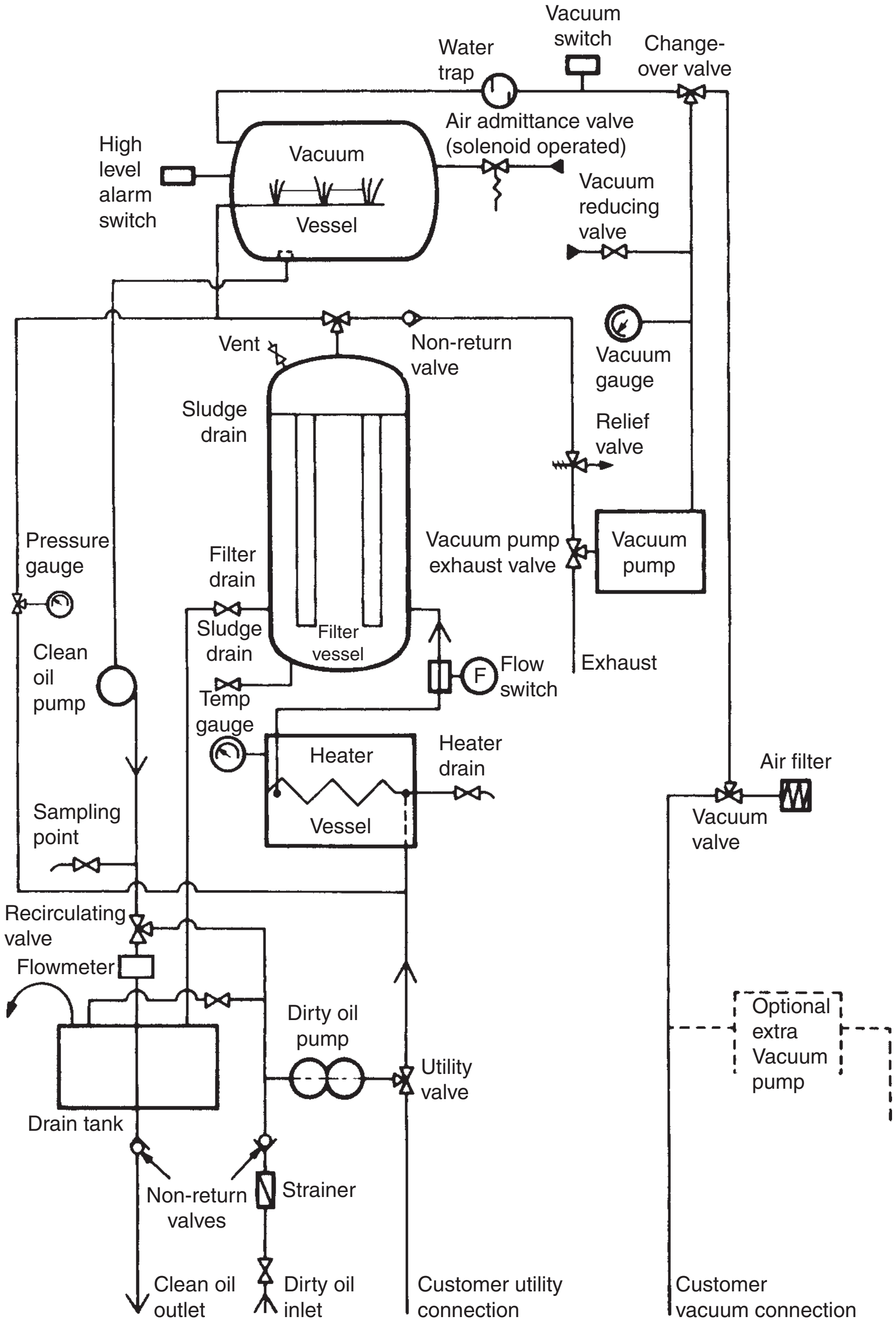


Figure 5.26 Flow schematic for insulating oil treatment

usually not very large, while system pressures are normally high, with exacting demands, both in terms of particle size and particle quantity, on freedom from solid contamination. The critical importance of hydraulic systems can be seen from the very large number of standards that exist covering equipment design and operation, starting with a glossary of terms used in hydraulics.

All hydraulic systems are contaminated, although the level of contaminant varies considerably depending on the environment and the use for which the system exists.

Earlier industrial hydraulic systems operated at pressures of 100 bar or less, and usually performed satisfactorily with minimal attention to filtering. Often a simple strainer on the pump discharge, or a filter with a cut-off of 25 to 50 μm, provided adequate protection. Some systems, in fact, dispensed with a filter entirely, instead withdrawing oil periodically for batch filtration and return to the system.

Most modern hydraulic systems operate at much higher pressures, up to 1000 bar working pressure, with flows up to 1000 l/min, with pumps having tighter clearances, and control valves and servos with even smaller clearances. The combination of higher pressure and reduced clearances calls for the elimination of particles from the system that could cause clogging and consequent system failure, requiring protection by finer filters. The general use of smaller reservoirs gives more rapid circulation of fluid and, thus, less opportunity for particles to settle out of the fluid flow. Higher fluid operating temperatures will mean reduced oil viscosities and less protection against wear, contributing to increased contamination generated within the system. Erosion can be a very real problem in high pressure, small bore systems, as localized fluid velocities may be as high as 650 km/h or more. This can lead to rapid wear on hardened and polished surfaces adjacent to high velocity fluid streams, even when particles of only 3–5 μm are present in the fluid.

In fact, in excess of 70% of hydraulic system failures are caused by contamination or poor fluid condition. Hence filters are essential in modern hydraulic systems, to provide a particular or specified level of contaminant removal. This can vary with the type of system, types of components involved, application and duty cycle.

Industrial applications

Almost every sector of industry, from large-scale manufacturing plants to small factory units, depends on reliable machine operation for productivity and profitability.

Machine tools have exacting accuracy and control requirements. Close tolerance control valves demand high standards of cleanliness and reliability. Low pressure, low viscosity fluid systems for coolants, cutting lubricants and washing machines need to be maintained at high levels of cleanliness. Injection and blow moulding machines depend on clean hydraulic fluid to work at high speeds and economically. Engineered hydraulic filtration is essential if machines are to work efficiently.

Hydraulic system filters are used to considerable effect for a wide range of automotive and mobile applications, including constantly variable, automatic and hydrostatic transmissions, active, anti-roll and automatic ride height suspensions, and other power transmission systems.

Aluminium-free hydraulic filters are used extensively in the mining industry for various applications, including roof supports, tunnelling and drilling machines, shearers, materials handling equipment, locomotives, hydraulic power packs, winches and haulages.

In the power generation industry, equipment failures can be disastrous and the highest standards of cleanliness are needed to protect system components and prevent malfunction of essential safety control systems. Hydraulic filters are also used extensively on off-shore rigs and in the production of industrial chemicals.

In the oil industry, hydrostatic transmissions on cranes, winches, well servicing equipment and so on, are fitted with hydraulic filters to help eliminate contamination-related pump or motor failures, and to increase valve service life. Hydraulic filters are used to protect rotating machinery in petrochemical plants, such as turbines, pumps and compressors.

Equipment range

In a broad sense, hydraulic filters may be described as high pressure, medium pressure and low pressure filters. High pressure filters will operate in excess of 400 bar working pressure, with flows of 450 l/min (although some operate to more than 1000 bar and for flows up to 1000 l/min). They can be manifold mounted and include both single and duplex housings.

Medium pressure hydraulic filters are suitable for a variety of pressure and return line applications. Typically, they can operate up to 250 bar maximum working pressure, with flows up to 800 l/min. They are often used as an alternative to spin-on filters, which can sometimes be underspecified for tough cyclic operating conditions.

Low pressure hydraulic filters are typically designed for operating pressures up to 28 bar, with flows up to 1200 l/min. Generally they have a wide application range, particularly for industrial and mobile applications, including high flow tank top and tank top return line filters. Many versions are of the spin-on type and can be provided as dual flow assembly off-line filtration. Core-less low pressure filter elements contain no metal and are designed to minimize waste disposal.

Low pressure off-line units are capable of measuring fluid temperature as well as element condition. Generally they operate at around 7 bar working pressure with flow rates up to 115 l/min. Portable hydraulic filtration systems are designed for on-site maintenance of fluids systems. An internal pump draws fluid through a primary clean-up filter and then through a polishing filter to remove contamination down to 3 μm absolute. Flow capacities are around 28 l/min.

A considerable proportion of hydraulic filters are of the in-line strainer type (Figure 5.27), with an easily replaceable cartridge element, very often supplied in duplex form so that the element in one can be changed, while the other keeps filtering. The most common medium is a pleated paper or nonwoven sheet, fitted with protective layers front and back to provide the necessary strength (Figure 5.28).

Figure 5.27 Hydraulic system filters

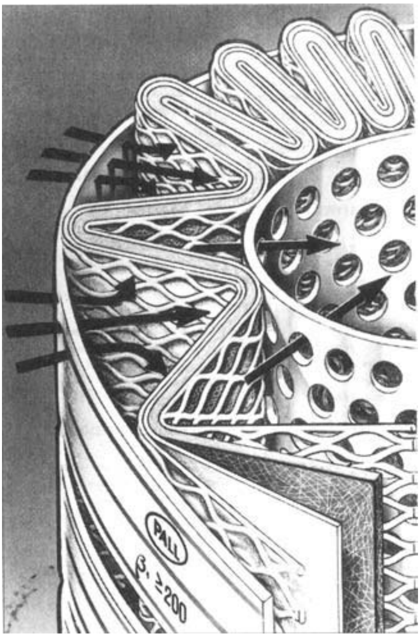


Figure 5.28 Hydraulic oil filter element construction

Contaminant levels

Filters fail because they either burst open or clog up. If a filter is left in a hydraulic system long enough, one or other of these two failure mechanisms will occur. For the precise needs of hydraulic system design, a suitable scheme for representing contaminant levels is required.

It could be argued that, if the system is built clean, has good filtration control and is able to run for a specified period, it might be economically sound to let it run unmonitored. Indeed, such systems do exist: fluid power guidance systems on missiles and space vehicles are built in extremely clean areas, with the components and total circuits being sampled for contamination. Contaminant levels in these cases are very low for obvious reasons. Missiles, once activated, might be short-lived, but that is no argument for relaxing controls in system cleanliness; besides, an inadvertent return of a missile to the sender would have disastrous consequences.

A space vehicle, on the other hand, is not short-lived and once launched will need to look after itself for months or years. Most satellites have guidance methods that involve the measured release of hydrazine through servo-type valves. These valves are similar in piston-to-sleeve clearance design to those used in aircraft flying power controls and super accurate machine tools, but this does not mean that the same contaminant level will suit all these systems.

The set of contaminant levels given in Table 5.5 (CONPAR) for various precision applications is that most commonly used in the UK. Table 5.5 does not make a clear distinction by number in absolute terms, but does show the wide ranging particle size distributions. Contaminant levels here are derived *from* filter performances, and since filters can be used under different conditions of flow, pressure and temperature, there is a difference usually between a filter test rating and a filter in service. This explains the particle populations in the table to some degree, for they were derived initially from real systems and then sequentially integrated through a statistically skewed component, producing a cleanliness factor to give a filter-particle-passing quantic, the exponential characteristics of which conform to nature in the context of a particle size and count distribution, but allowing flexibility (±) provided that the exponential or natural aspect is never ignored.

CETOP RP70 system

The CETOP RP70 system is merely a method of expressing sample particle counts in terms of a simple code, as in Table 5.6. It does not specify the method of sampling or making the count, nor does it indicate the type or geometry of the contaminants. Particles are grouped according to size, so that the count for each size group can be specified by range number. In practice, only two parameters are normally used (although this may vary when applied to specific systems). These are the total count of all particles above 5 µm, and the total count of all particles above 15 µm.

Each count is then allocated a range number and the contaminant level expressed as these two numbers separated by a forward slash (solidus), thus: 16/10. This represents a particle size distribution with a count of between 32,000 and 64,000 of all

Table 5.5 Contaminant level classes

	Satellite			Missile			Sub-miniature servo-valves, some aircraft oils as new		
	Particles per 100 ml by dirt contamination class								
Size range	Class 1-H			Class 2-H			Class 3-H		
µm	Class (red)	'Tol' (green)	% Distrib	Class (red)	'Tol' (green)	% Distrib	Class (red)	'Tol' (green)	% Distrib
+100	7	2	0.015	7	2	0.0015	7	2	0.0007
50–100	15	4	0.044	15	4	0.0030	15	5	0.0016
25–50	94	27	0.279	104	29	0.0230	133	40	0.0140
15–25	290	64	0.836	370	71	0.0830	529	160	0.0570
10–15	701	180	2.086	1810	518	0.4060	3677	1128	0.4010
5–10	1617	415	4.812	22,320	6377	5.0190	50,050	15,167	5.4730
1–5	30,882	7918	91.899	420,000	120,000	94.4610	860,606	260,780	94.0530
Cum. Total	33,606	8610		444,626	127,001		915,017	277,282	

	Miniature servo-valves			High pressure industrial and hydrostatic transmission systems					
Size range	Class 4-H			Class 5-H			Class 6-H		
µm	Class (red)	'Tol' (green)	% Distrib	Class (red)	'Tol' (green)	% Distrib	Class (red)	'Tol' (green)	% Distrib
+100	22	7	0.0007	32	11	0.0003	43	17	0.0002
50–100	51	15	0.0016	89	31	0.0009	128	51	0.0008
25–50	439	133	0.0140	829	268	0.0090	1220	488	0.0080
15–25	1744	529	0.0570	3480	1200	0.0380	5220	2088	0.0340
10–15	12,137	3677	0.4010	29,143	10,050	0.3220	42,181	16,870	0.2800
5–10	165,168	50,050	5.4730	450,864	155,470	4.9800	714,240	285,696	4.7480
1–5	2,840,000	860,606	94.0530	8,568,000	2,954,630	94.6370	14,280,000	5,712,000	94.9270
Cum. Total	3,019,561	915,017		9,052,437	3,121,660		15,043,032	6,017,210	

(*Continued*)

Table 5.5 (Continued)

	Rough industrial earthmoving equipment and similar								
Size range	Class 7-H			Class 8-H			Class 9-H		
µm	Class (red)	'Tol' (green)	% Distrib	Class (red)	'Tol' (green)	% Distrib	Class (red)	'Tol' (green)	% Distrib
+100	47	20	0.0002	57	30	0.0002	68	35	0.0002
50–100	147	64	0.0008	185	97	0.0007	224	118	0.0007
25–50	1415	615	0.0078	1805	950	0.0074	2196	1155	0.0075
15–25	6090	2648	0.0337	7830	4121	0.0325	9570	5036	0.0327
10–15	50,442	21,831	0.2795	67,240	35,390	0.2793	84,051	44,237	0.2874
5–10	857,088	372,646	4.7492	1,142,784	601,465	4.7483	1,428,480	751,831	4.8840
1–5	17,136,000	7,450,434	94.9540	22,848,000	12,024,737	94.8300	27,720,000	14,589,473	94.7800
Cum. Total	18,051,229	7,848,258		24,067,901	12,666,790		29,244,589	15,391,885	

MOD (RN) Central Hydraulic Authority equivalents to Conpar are:

RN 400 = 2-H
RN 800 = 3-H
RN 1300 (no equivalent)
RN 2000 = 4-H
RN 4400 = 5-H
RN 6300 = 6-H
RN 1500 = 9-H, basically cumulative values above 15 µm

particles above 5 µm in size in a 100 ml sample, together with a count of between 500 and 1000 particles above 15 µm in size in the same 100 ml sample. Table 5.7 is the reverse of Table 5.6, giving a useful reference for converting code numbers into actual particle counts over the range likely to be encountered in practice.

Table 5.6 CETOP particle count code system

Number of particles per 100 ml	RP70 Range number
1–2	1
2–4	2
4–8	3
8–16	4
16–32	5
32–64	6
64–130	7
130–250	8
250–500	9
500–1000	10
1000–2000	11
2000–4000	12
4000–8000	13
8000–16,000	14
16,000–32,000	15
32,000–64,000	16
64,000–130,000	17
130,000–250,000	18
250,000–500,000	19
500,000–1,000,000	20
1,000,000–2,000,000	21
2,000,000–4,000,000	22
4,000,000–8,000,000	23
8,000,000–16,000,000	24

Table 5.7 CETOP count code interpretation

Code	Larger than 5 µm	Larger than 15 µm
10/8	500–1000	130–250
11/8	1000–2000	130–250
12/8	2000–4000	130–250
12/9	2000–4000	250–500
13/8	4000–8000	130–250
13/9	4000–8000	250–500
13/10	4000–8000	500–1000
14/8	8000–16,000	130–250

(*Continued*)

Table 5.7 (Continued)

Code	Larger than 5 µm	Larger than 15 µm
14/9	8000–16,000	250–500
14/10	8000–16,000	500–1000
14/11	8000–16,000	1000–2000
15/9	16,000–32,000	250–500
15/10	16,000–32,000	500–1000
15/11	16,000–32,000	1000–2000
15/12	16,000–32,000	2000–4000
16/10	32,000–64,000	500–1000
16/11	32,000–64,000	1000–2000
16/12	32,000–64,000	2000–4000
16/13	32,000–64,000	4000–8000
17/11	64,000–130,000	1000–2000
17/12	64,000–130,000	2000–4000
17/13	64,000–130,000	4000–8000
17/14	64,000–130,000	8000–16,000
18/12	130,000–250,000	2000–4000
18/13	130,000–250,000	4000–8000
18/14	130,000–250,000	8000–16,000
18/15	130,000–250,000	16,000–32,000
19/12	250,000–500,000	2000–4000
19/13	250,000–500,000	4000–8000
19/14	250,000–500,000	8000–16,000
19/15	250,000–500,000	16,000–32,000
19/16	250,000–500,000	32,000–64,000
20/13	500,000–1,000,000	4000–8000
20/14	500,000–1,000,000	8000–16,000
20/15	500,000–1,000,000	16,000–32,000
20/16	500,000–1,000,000	32,000–64,000
20/17	500,000–1,000,000	64,000–130,000

ISO 4406 cleanliness standard

The ISO 4406 solid contaminant cleanliness code is used by components manufacturers and technical institutions as the internationally accepted method of quantifying the numbers of particles present in a sample of fluid. Automatic particle counters are used to analyse the particle size distribution of all contaminants in a sample within specified size ranges. All particles, magnetic or non-magnetic, metallic or non-metallic, are detected, giving the total contaminant level of the sample.

The practice of monitoring this dirt level in existing systems has become an effective way to confirm whether the correct filter selection has been made. The designer should use either of the following two sets of data when considering system cleanliness:

- the hydraulic component manufacturer's recommendation for component sensitivity (the best supplier's data specify component sensitivity in terms of fluid cleanliness level as an ISO class number, or as the number of particles larger than 10 µm per ml of fluid; if data are not available from the component supplier, then Table 5.8 can be used), or

Table 5.8 Typical fluid cleanliness levels

Component	ISO 4406 Classification
Servo control valves	14/11
Vane and piston pumps	16/13
Gear pumps	17/14
Common control valves	18/15

- results of a recent contamination control research programme (in which the contamination levels were monitored in some 120 varied systems, sub-divided into specific machine categories; the average contamination levels experienced, which can be considered to be those that are acceptable from a reliability point of view, are detailed in Table 5.9).

Table 5.9 Acceptable contaminant levels

System category	ISO 4406 Contamination levels
Injection moulding	16/11
Metal working	16/11
Machine tools	15/9
Mechanical handling	18/13
Mobile	18/11
Aircraft test stands	13/10
Marine installations	17/12
Unused oil	16/11

Contaminant level test results are obtained from a test rig such as that shown in Figure 5.29, which shows a hydraulic bearing cylinder under test. ISO range numbers are effectively the same as the CETOP numbers given in Table 5.6.

Once a required cleanliness range has been determined, to which a hydraulic system reliability can be directly related, the final task is to select correct cost-effective filters that retain the contamination level balance in the system, i.e. the total number of particles generated in the system is equal to (or less than) the total number of particles removed.

The levels in practice

The use of a filter with a specific rating consistent with the requirements of the system does not necessarily imply satisfactory performance. Apart from the fact that

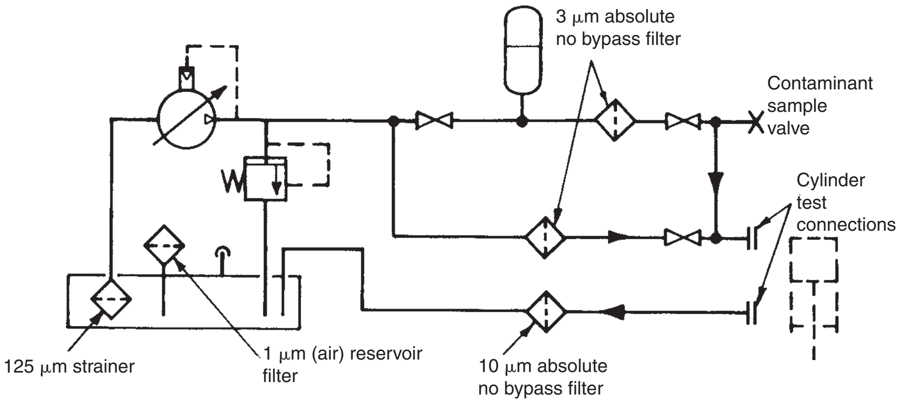


Figure 5.29 Particle test rig circuit

the filter will be less than 100% efficient under working conditions, particularly if pulsating flow is present, contaminant particles may be dislodged from the pores of the filter element allowing more fine particles to pass through. In critical or sensitive systems, therefore, monitoring of the contaminant level will be desirable, with suggested contaminant level maxima shown in Figure 5.30.

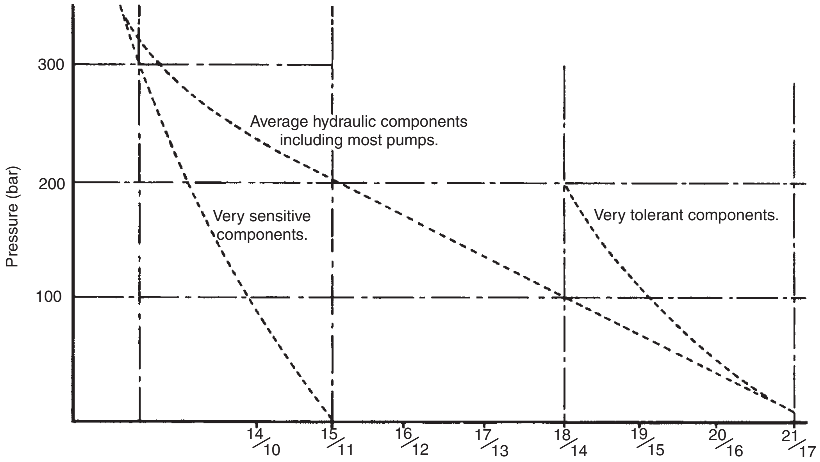


Figure 5.30 Contaminant level maxima

The object of monitoring is twofold. First, to check that contaminant accumulation does not exceed an acceptable level, and possibly from this to establish what is an acceptable contaminant level in the absence of available guidelines. Second, to check that the initial filter specification is adequate for the system in practical use. Here, it should be mentioned that it is not necessarily just the filter which is involved.

The system pressure and duty cycle, and the location of the filters, are additional parameters that can influence contaminant level. Intelligent attention must also be given to the points in the system from which fluid samples are drawn for analysis when measuring contaminant levels, and to the method of extracting the fluid samples. Thus, the system should have been operated for at least 30 minutes to distribute contaminants uniformly before sampling, and if the sample is drawn from a valve, a flushing flow should be drawn off first, before taking the actual sample. Alternative sampling points are a sampling tank fitted with a clean valve (such as a ball valve with PTFE seat), or possibly the reservoir in the case of hydraulic systems. In all cases, samples should only be taken under the cleanest conditions possible.

Sampling kits, such as the one shown in Figure 5.31, provide access to fluid systems at working pressure. This particular unit is capable of presampling (flushing) and sampling so that the particles from 100 ml of the active fluid system can be collected on an 0.8 μm membrane. The sampling and direction control valves in this particular design prevent external contamination, and the filtered air porting on the valve block provides a means of syringing the membrane dry *in situ*. The sampling monitor is then removed and evaluated through a microscope, by checking the sample against the master slide modules. Current microscopes of this kind are now equipped to analyse samples by a unique system of lighting, coupled to an offset rotary stage for the controlled movement of ferrous particles within the particle pattern on the sample. The magnetic field is just powerful enough to move iron

Figure 5.31 Contaminant sampling kit

particles without disturbing the particle pattern. This makes it possible to analyse a contaminant level on a comparative basis by judging the sample against the red and green master slides of the system, and then identifying the particulate as ferrous, non-ferrous or silica via the combined systems of transmitted, reflected and polarized light, used in conjunction with the magnetic field device.

This field analysis method produces answers regarding contaminant level and nature in minutes, rather than the hours and days required when samples are sent to a laboratory for processing. It also overcomes the ever-present problem of artifacts: those particles that creep into the picture at each process step. Bottle sampling is a good example since, once transfers begin, it becomes virtually impossible to exclude the particles that are present in the air and on the components used to process the sample membrane into a readable unit. The artifact problem will remain a problem if a cross-contaminated bottle sample is processed by an automatic particle counter, where the only result possible is particle size and count. An assessment via a microscope improves matters since the artifacts may be recognized as something not usual to the sample. On-line particle counting will eventually overcome the artifact problem, and devices to judge particle build-up against a time base will soon become common. They will supply an answer to what is perhaps the most difficult question, that is the performance of a filter in use as distinct from its performance in set tests. These on-line devices will eventually be integrated with monitoring systems, to obtain correlation, calibration and qualitative support for the real-time contaminant levels that will be shown.

Patch tests

The patch test method of monitoring the degree of particulate contamination in liquids is undertaken by observing the discoloration of the surface of a 5 μm filter membrane, through which a standard volume of liquid has passed. PVC bottles (120 ml) are used to collect the sample, and this is then processed via a stainless steel funnel filter holder and flask under vacuum. Care is needed in processing as rinsing solvents must themselves be filtered to avoid cross-contamination. Care is also needed to prepare the equipment for re-use.

When the sample has been processed, the result exists as a patch (or stain) on a 5 μm (usually ungridded) membrane, and this is then matched to a membrane filter colour rating scale, based on quantitative and/or gravimetric levels of contamination. Accuracy levels by this method are lower than those obtained in methods such as the one previously described. The reason for the higher accuracy of the Conpar method is almost certainly the closer control of the membrane (0.8 μm) coupled with a viewing system that is, at its lowest point, 50–100 times better than the naked eye.

Counting

Particles must be distributed evenly on to sampling membranes in order to gain accurate, statistically based casting methods. For example, a Class 6-H level viewed at ×50 expansion will show over 7000 particles between 5 and 10 μm in a 3 mm net, and the result where counting is concerned is just a dense group of particles. Moving to ×100 reduces the example net to 1750 particles, and if magnifying power continues to increase, then it becomes possible accurately to count particles in a discrete size range. Much easier to view is the projection microscope, which projects and enlarges the specimen onto a screen. This microscope has a modified stage to orient the solid particles and the grid lines on the specimen with co-ordinates taken from the inscribed verniers on the stage. The sizing of the particulate is achieved by a filar micrometer eyepiece, operating at the upper focal plane of the objective to project lines that define the maximum and minimum limits, to permit the sizing of solid particles in size ranges within the range of 1 to 1000 μm.

Although this instrument is widely used, and commonly known as a back projection microscope, it does not project an image through a screen such as a Fresnel, but transmits the image to an over eyepiece prism, and out at 90° onto a super-flat white screen with fixed lines on its surface. The combination of a high quality image and a high accuracy measuring filar eyepiece brings particle counting and sizing out in the open so that more than one operator can see the picture at the same time.

When levels are being considered as a means of control, it must always be borne in mind that quantitative analysis must be accompanied by qualitative findings as well. Apart from the standard microscopical checks for ferrous and ferric oxides, aluminium and silica, chemical analyses are used to establish acid and water levels in the carrier fluid. If this is insufficient, the analysis is then extended to one or more of the following techniques:

- atomic adsorption spectrophotometry
- infra red microscopy
- laser Raman analysis
- phase contrast microscopy
- pyrolysis gas chromatography, and
- scanning and transmission electron microscopy with wavelength and energy.

System contaminants

Contaminants within a typical hydraulic system may be derived from both external and internal sources. Contaminants from external sources include those introduced during manufacture and repair of components, and assembly of the system. These may include casting sand, drawing compounds, welding fumes, machining chips and loose burrs, elastomeric particles from seals and gaskets, assembly compounds, adhesives, and even paint particles. Such particles may range in size from 1 to 500 μm. Additionally, airborne dust and dirt, rust and other forms of corrosion products may be implanted contaminants with a similar size range.

The environment is a major source of external contaminants during the construction and working of the system, typical entry points for such contaminants being:

- air breathers
- rod seals on hydraulic cylinders (particularly in dirty atmospheres and/or with increasing seal wear)
- access plates and other detachable items, and
- hydraulic reservoirs (during fluid volume changes).

The system fluid may be a further source of external contamination. New oil as refined and blended is clean (contaminant free), but if stored in a bulk tank or in drums is subject to contamination from metal and rubber particles in the filling lines, and possibly metal flakes or scale from the container itself. Water condensation within tanks further contributes to contamination by corrosion products. Typical contaminant size in fluids is 3 to 10 μm, but much larger particles may be present in bad cases.

Bulk storage of fluid

Actual contamination arising from delivery and storage varies widely with the industry. The highest standards of cleanliness are achieved in the aircraft industry using small containers with a quick turnover of stores. The least satisfactory are industrial systems storing bulk fluid under unfavourable environmental conditions for long periods before use. Outside storage is not recommended. Drums containing hydraulic fluid should be kept indoors in a clean, well-ventilated area. They should be stored in a horizontal position and supported off the ground to prevent the metal container from corroding. If the drums are to be used in a horizontal position, the bung should be replaced by a suitable tap whilst the drum is vertical, then the drum should be supported horizontally by a cradle.

The preferred method of extracting hydraulic fluid from containers is by the use of a portable pump and filter unit, or by means of an off-line filtration unit fitted to the system. The filter unit of the portable system should be checked to ensure that it has the correct rating.

Internal contaminants

Contaminants from internal sources, i.e. those generated within the working system can be numerous, including:

1. abrasive wear, typically 5–250 μm
2. galling (adhesive wear), typically 5–750 μm
3. contamination and erosion, typically 40–250 μm
4. surface fatigue, typically 5–50 μm
5. metallic salts produced by:
    - rust and corrosion, typically 5–150 μm
    - electrolysis, typically 5–250 μm
    - water contamination, typically sludge
6. fluid degradation particles (typically 0.2–150 μm), varnish, carbon particles, acids, sludge and microbiological growths.

A further source of internal contaminants is from particles escaping from or unloaded by the filters in the system. These may be of any of the aforementioned types originally retained by the filter. A condition very often ignored is vibration of the filter unit. It is advisable to use flexible mountings to isolate the filter and flexible hoses in place of rigid pipe work to separate a filter from a pump or actuator, in order to minimize vibration to filter assemblies.

Effect of contaminants

The majority of contaminants likely to be introduced into a hydraulic system from external and internal sources are abrasive, and the resulting wear accounts for about 90% of the failures due to contamination. (The remainder is caused by clogging by sludges.) Particles most likely to cause wear are those of a clearance size, which just pass through clearance spaces between moving parts. Larger particles cannot enter such spaces (although they can contribute to clogging, or even cause jamming). Smaller particles can pass through clearance spaces without necessarily abrading the surfaces, unless present in large quantities. The degree of protection provided by filtration is thus directly related to the clearance spaces within the system.

Specifically particles larger than 25 μm are called chips, and particles between 3 and 25 μm are called silt. Reference may then be made to filters providing silt control (3–5 μm absolute rating), partial silt control (10–15 μm absolute rating) and chip control (25–40 μm absolute rating).

Protection levels

Typical clearances employed on hydraulic system components range from 15–40 μm for low pressure components, down to about 5 μm for high pressure components (or even less for miniature valves), as shown in Table 5.10. Most components will have critical areas, which are particularly subject to clearance problems. Examples include:

- gear pumps – tooth to housing, and gear to side-plate clearances
- vane pumps – vane tip and motor to side-plate clearances
- axial piston pumps – cylinder block to valve plate, piston to cylinder and slot to swash-plate clearances
- spool valves – eccentricity (resulting in varying clearances)
- throttle valves – orifice shape (a groove type orifice is less prone to silting)
- poppet valves – valve seat (erosion).

If 25 μm is accepted as a general level of protection required for low pressure industrial hydraulic systems, and in the absence of specific requirements from the component manufacturers, the filter ratings given in Table 5.11 are recommended for different systems.

Hydraulic system filtration requirements

The basic requirements of a filtration system for hydraulic services are as follows:

- it should be capable of reducing initial contamination present in the fluid and/or system to the desired level, within an acceptable period of time

Table 5.10 Hydraulic system component clearances

Component Item (µm)	Typical clearance (ml)	
Gear pumps (pressure loaded)		
Gear tip to case	0.5–5	0.02–0.2
Gear to side plate	0.5–5	0.02–02
Fixed side clearance	25–50	1–2
Vane pumps		
Vane tip to case	0.5–1	0.02–0.04
Vane side to case	5–13	0.2–0.5
Piston pumps		
Piston to bore (radial)	5–40	0.2–1.6
Valve plate to cylinder	0.5–5	0.02–0.2
Control valves		
Spool to sleeve (radial)	1–23	0.04–0.9
Spool		
Spool to bore	5–13	0.2–0.5
Disc	0.5–10	0.02–0.04
Poppet	13–40	0.5–1.5
Orifice	130–10,000	5–400
Servo valves		
Spool to sleeve (radial)	1–4	0.04–0.16
Flapper	18–63	0.7–2.5
Orifice	130–450	5–18
Cylinders		
Piston to bore	50–250	2–10
Rod bearings	1.5–10	0.06–0.4
Motors (see Pumps)		
Actuator bearings		
Plain/sliding bearings	1.5–10	0.06–0.4
Rolling bearings	1.5–10	0.06–0.4

Table 5.11 Hydraulic filter ratings

Filter rating	µm
Low pressure systems with generous clearances	25–40
Low pressure heavy duty systems	15–25
Typical medium pressure industrial systems	12–15
Mobile hydraulic systems	12–15
General machine tool and other high quality systems	10–12
High performance machine tool and other high pressure systems where reliability is critical	3–5
Critical high pressure systems and controls, using miniature components	1–2

- it must then be capable of maintaining the desired level of contaminant removal over a suitable period (i.e. have sufficient dirt-holding capacity), and
- the filters in the system should incorporate some form of indicating device to show their state in use.

The filters themselves should also have the following properties:

1. adequate element strength and freedom from migration
2. an adequate contaminant retaining capacity
3. adequate size for the required maximum flow rate
4. low back pressure or pressure drop across the filter
5. low pressure drop relative to flow rate (i.e. low pressure drop to flow ratio)
6. performance maintained over a suitable temperature range (bearing in mind the change in fluid viscosity over that range)
7. component parts suitable for and compatible with the hydraulic fluid concerned
8. low weight
9. compact size
10. an ability to withstand high pressure surges, or high pressure differentials, without rupturing or permitting bypassing of the medium
11. compatibility with standard system components
12. a design that permits rapid servicing (i.e. easy cleaning or replacement of the element)
13. economic cost (both initial and lifetime costs).

Other specific requirements may be mandatory in certain hydraulic systems, such as bypass characteristics to maintain flow in the event of the element's becoming clogged, or alternatively visual or audible warning when the filter element requires replacement, or even automatic shut-down to ensure that unfiltered oil is not circulated through the system.

Filter types

Examples of the wide range of types of filter element used in hydraulic filters are given in Table 5.12. Pleated cellulosic paper and woven wire mesh are widely favoured, but can only provide partial silt control. Sintered porous metal and glass microfibre media are capable of providing full silt control. The latter type (glass microfibre) is now used as a medium for both chip control and silt control filters. It offers good pore size distribution, greater open area than cellulose or wire mesh media because of the smaller fibre diameter, and better dirt-holding capacity. Its chief disadvantage is that it is low in strength, although this can be enhanced with resin treatment. It is normal practice to support glass microfibre elements on both the upstream and downstream sides.

Some examples of pleated wire mesh elements for hydraulic filtration use are illustrated in Figure 5.32.

Element strength and construction can affect the choice of medium, a range of media being shown in Table 5.13. Elements of very low mechanical strength are precluded from high pressure applications. Even if backed by a rigid screen, or otherwise rigidly reinforced, there is still the possibility of element fibre migration, or

Table 5.12 Hydraulic filter element types

	Minimum article size retained (μm)								
	Nominal	Absolute	Pore size control	Flow capacity	Dirtholding capacity	Resistance to migration	Mechanical strength	Consistency	Cost
Wire gauze		60–100	F	H	P	VG	VG	VG	L
Shaped wire		60–80	F	H	F	VG	VG	VG	M
Metal disc (stack)		60–100	F	H	F	VG	VG	VG	M
Felt (pad)	30–40		P	M	G	P	P	F	L
Felt (pleated)	25–35		P	M	G	P	L	F	L
Paper (pleated)	10–20	25–35	F	VL	F	P	P	F	L
Impregnated (papers)	10–15	10–35	F	VL	F	P	P	F	L
Paper ribbon	50–100		F	M	G	P	F	G	M–L
Paper disc	5	20–25	F	L	G	F	L	F	M–L
Woven wire mesh	5	10	VG	M	P	VG	H	G	H
Woven wire cloth	5	10	VG	F	P	VG	H	VG	VH
Wire cloth and paper		10–25	G	L	P	G	F	G	H
Glass microfibre	1, 2, 3	1, 2, 3	M	H	H	P	L	VG	L
Sintered metal	2, 5 or 10	2, 5 or 10	VG	M	F	VG	VG	VG	M–L

Key: G, good; L, low; P, poor; F, fair; H, high; M, moderate; VG, very good.

Figure 5.32 Wire mesh elements

of localized failure under pressure surges. Table 5.13 still includes asbestos as a filter medium, now completely phased out because of its toxic properties. Excluded from the table is any mention of spunbonded or other modern extruded fibre material – these have very good filtration properties, but are mostly not strong enough for hydraulic duties.

It should be appreciated that, even in a high pressure system with steady flow, the pressure that the filter element strength is required to withstand is only that of the maximum pressure drop across the element (with a suitable safety factor), although the filter body will have to withstand the full system pressure. Pressure surges occurring in the system may (momentarily) increase the differential pressure across the element by a substantial amount, but not to the limit of the surge pressure (unless the filter is completely clogged), this figure being applied only to the filter body. In all cases, the actual physical pressure applied to the filter element can only be the differential pressure realized across the element – hence the fact that comparatively low strength materials can be used for high pressure filters. On the other hand, certain types of filter element are capable of withstanding extremely high differential pressures, of the same order as line pressures, in which case they can be referred to as true high pressure elements.

Table 5.13 Types of filter element

Element	Approximate filtration range µm	Remarks
Felt	25–50	Subject to element migration unless resin-impregnated.
Paper	Down to 10 or better	Low permeability, low element strength. Subject to element migration.
Fabric	Down to 20	Higher permeability than papers. Higher strength with rigid back-up mesh, etc.
Wire gauze	Down to 35	Suitable for suction strainers, tank strainers, etc.
Wire wound	Down to 25	Good mechanical strength.
Wire cloth	Down to 10	Expensive, but well suited to high pressure systems with high strength and freedom from migration.
Edge type (ribbon element)	40–70	Low resistance to flow with reasonable strength (self-supporting).
Edge type (paper disc)	10 down to 1 or better	Degrees of filtration variable with compression. High resistance to flow. Clogs readily.
Edge type (metal)	Down to 25	Very strong self-supporting element; suitable for high temperatures, *i.e.* full systems pressures.
Sintered woven wire cloth	10–20	High strength, suitable for high temperatures. Complete freedom from element migration. High cost. Low dirt capacity.
Glass microfibre	Down to 3 or better	Modern preferences for silt control filters – superior performance to cellulosic fibres and wire meshes.
Asbestos fibre	Down to 3 or better	Effective as silt control filters, but decreasing application because of possible carcinogenic rating.
Sintered porous metal	Down to 2.5	Good mechanical strength, self-supporting and suitable for high pressures and temperatures. Low dirt capacity. Element migration not entirely eliminated under severe conditions.
Sintered porous metal with woven wire reinforcement	Down to 2.5	Very high strength. Suitable for full line pressures.
Sintered PTFE	5–25	High cost, subject to element migration. Strength improved by reinforcement.

(*Continued*)

Table 5.13 (Continued)

Element	Approximate filtration range µm	Remarks
Sintered polythene	30	Low resistance to flow and freedom from element migration. Not suitable for temperatures above 60°C (140°F).
Sintered metal felts	Down to 5 or better	High cost, but freedom from element migration. Difficult to clean (elements usually replaced).
Membrane filters	Down to submicrometre sizes	Low mechanical strength and poor dirt capacity. Main use is for extreme cleaning of test rigs, etc., or oil reclaiming.
Magnetic filters	Ferrous particles	Little or no resistance to flow.
Filter mats (cellulose, etc.)	Down to 0.5	Used in batch filters or prefilters.
Filter cloths	Down to 10 or better	May be used in batch filters or air breathers.

Electrostatic filters

Electrostatic off-line filters remove only a small proportion of particulate matter on each pass and therefore have a low β ratio. However, they remove a great deal of contaminant over a long period and have a high dirt-holding capacity up to 2 kg of contaminant. They are very effective at removing small particles down to 0.05 µm. In operation, typically, under the influence of an applied 10 kV voltage, contaminant particles in the fluid become charged and are attracted towards the appropriate electrode plate. Each electrode plate is covered with pleated paper collectors and these catch a proportion of the particulate. Performance additives completely dissolved in the fluid are unaffected by the electric field, but suspended additives may be removed. Operating costs of this purification method are low, mainly because there is no pressure drop in the system.

Element cleaning vs disposal

In general, low cost filter elements are regarded as disposable (that is by being replaced with a new element) as the cost of recleaning may be as high as, or higher than, that of the replacement element. Certain media may be difficult or almost impossible to clean anyway, or be susceptible to damage during the cleaning. The more robust media, such as wire mesh and sintered porous metal elements, are more economically recleaned and they may be used a number of times. Three to seven cycles of cleaning and re-use are typical, but the number depends on the service conditions and cleaning facilities available. The most suitable cleaning system for such types is an ultrasonic bath.

Filter location

Choice of position or positions for the filters in a hydraulic system is largely a matter for the individual designer to decide. On older systems a single filter was often fitted on the pump suction side, or inside the tank or reservoir. This had the advantage that the filter did not have to carry the full system pressure and was isolated from any surge pressures. However, the filter was of necessity fairly coarse and of large area, in order not to restrict flow to the pump, and if it did become clogged could cause the pump to cavitate, unless the flow was bypassed straight to the pump. This logical method of preventing pump cavitation meant that both the pump and system were fed with unfiltered fluid under such conditions. The one merit of such a system is that suction-type filters can be less robustly constructed and are thus less costly than pressure-type filters.

On many modern systems, however, the only filtration on the suction side of the pump is provided by a strainer in the tank or reservoir. These are so designed that adequate suction flow will be maintained under all conditions by attention to strainer and tank inlet and outlet pipes, so that cavitation conditions are avoided. This provides filter protection for the pump inlet.

Such inlet strainers, of course, do not remove any pump-generated contamination, which is then fed directly into the system on the pressure side. Equally, they are not necessary in systems with closed reservoirs, with silt-control filtration on the return line, or where fluid is introduced into the system upstream of the return line filter. Suction line filters are cheap, but do not usually have indicators to show when they are dirty or blocked.

Pressure line filtration

A pressure line filter is located on the delivery side of the pump and is thus exposed to full system pressure. It will protect the following system from pump-generated or pump-passed contaminants, but not from any contaminants generated within the hydraulic system downstream of the filter.

It is important to ensure that there is no reverse flow through the element due to valve maloperation or compressibility effects. Filters are available that incorporate special valving that allows fluid to pass through the element in one direction, but to bypass the element when the flow is reversed.

Three possible filter configurations are shown in Figures 5.33 to 5.35. Location of the filter before the relief valve gives constant flow through the filter (Figure 5.33). If the filter is located downstream of the relief valve, the flow through the filter will depend on system demand and in off-load periods will have leakage flow or full flow, depending on whether the control valve is of blocked-centre or open-centre type, respectively (Figure 5.34). Such positioning thus makes it more difficult to estimate the varying flow rates to which the filter may be subjected and so a bypass across the filter is essential, to eliminate excessive pressure build-up against the pump, should the filter become clogged (Figure 5.35).

Additional protection for the system can then be provided by further filters preceding critical components, or point-of-use filters at each working station. Filter

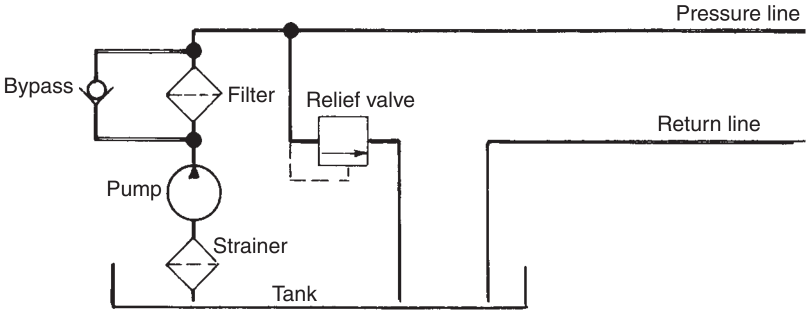


Figure 5.33 Constant flow system

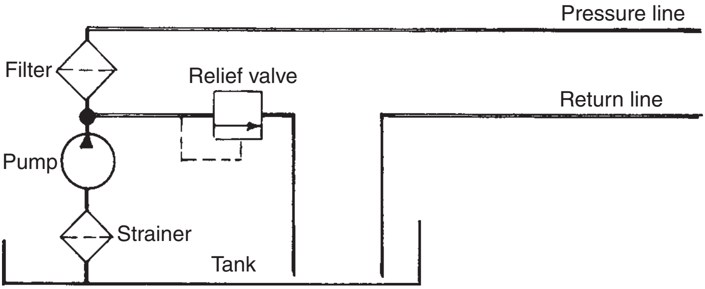


Figure 5.34 Non-bypass filter

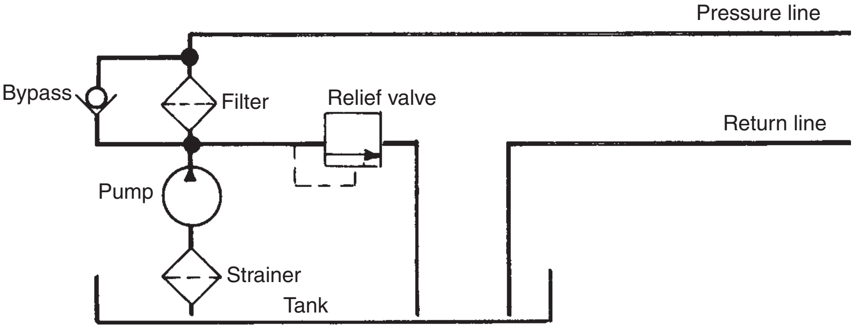


Figure 5.35 Filter with bypass

requirements can be selected in a number of different ways, depending on how critical protection is for each component of the system. If the first filter (following the pump) provides the necessary fine filtering, the first component in the system is protected. Subsequent components that need protection from contaminants, which may be generated by the first component, can be preceded by an additional fine filter. A component with more generous clearances, not needing such protection, does not have to have a point-of-use filter preceding it. Equally, a point-of-use filter could precede each component needing protection (chosen with a suitable rating) when the first filter following the pump could be of a coarser type for lower resistance to full pump flow.

Return line filtration

A return line filter is located downstream of the last working component in the system, but upstream of the reservoir (Figure 5.36). It thus removes all contaminants (down to its rating level) ingested or generated by the pump and system components before the fluid is returned to the reservoir. This positioning has the advantage that the filter is not likely to be subjected to the large pressure surges that can occur in the pressure lines, but it can be subject to unsteady flow conditions, and thus needs to be robust enough to accommodate such flow surges. Return line filters can be prone to contaminant shedding if there are shocks, surges, sudden valve operation or fluctuating operating conditions. Their position precludes their use as protective devices.

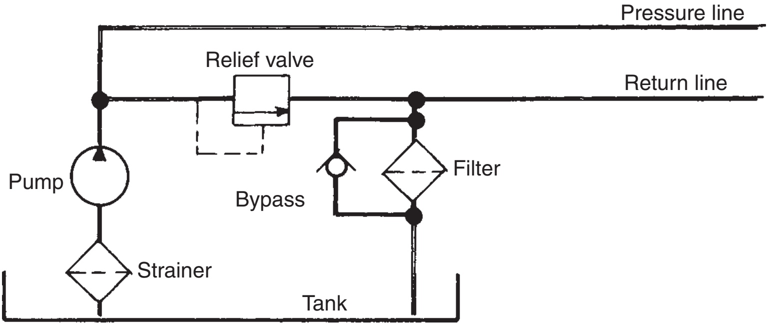


Figure 5.36 Return line filtration

Bypass filtration

A bypass filter is located in a separate loop between pump and reservoir, operating independently of the main system. Its purpose is to provide a means of cleaning fluid contained in the reservoir only (Figure 5.37). Its particular use is for overall fluid cleaning at suitable maintenance intervals. It can, if necessary, be operated when the main system is in use. It does not, of course, dispense with the need for filters in the main system, since it only cleans the amount of fluid present in the reservoir.

With bypass filtration in use by itself, only a proportion of the main flow is filtered and therefore the general level of contamination in the system would rise. The filter element life would generally be short, particularly if a smaller filter is matched to the lower flow rate. For example, if an electrohydraulic servo valve is being protected by its own small fine filter, the system must also include additional filtration.

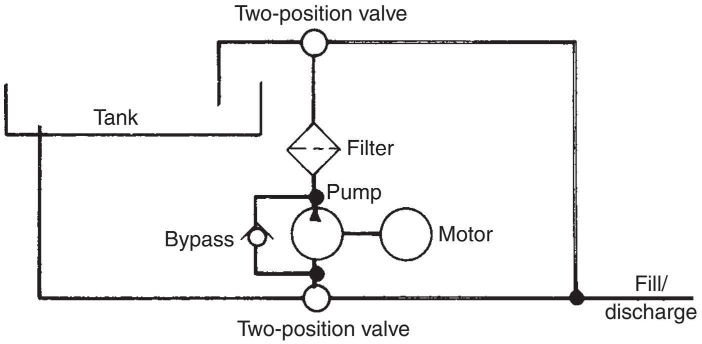


Figure 5.37 Bypass filtration

Off-line filtration

A convenient position for installing off-line filtration is in the reservoir. Care is required in positioning the tank connections to prevent any settled contaminant or water being re-entrained. This system may be combined with the filling system; it may be run as a clean-up system when the main pump is not in use, and should be running continuously when the main system is operating.

Filter maintenance may be carried out at any time without disturbing the main system. The filter elements are provided with a steady flow and there are no pressure fluctuations whatever in the system operating conditions. A self-contained unit with a motor driven pump and integral filter element may be fitted to the reservoir.

Batch filtration

Batch filtration is similar to bypass filtration in that fluid is drawn from the reservoir and passed through a filter before being returned for further use. This is carried out by an independent unit, which may be used to batch filter any number of separate systems.

These several operating modes are summarized in Table 5.14, in terms of filter position.

Filter selection

The filter medium and element construction employed for specific hydraulic filters is chosen on the basis of filter performance required, acceptable pressure drop, mechanical strength, compatibility with the fluid being used, and other working parameters.

Compatibility with the system fluid must relate to the system temperatures involved, to ensure that no degradation of the element or its seals occurs during its normal service life. Degradation can occur through any of the following:

- absorption of fluid into the filter medium or binder, causing swelling (and so increased pressure drop and choking) or migration of particles downstream

Table 5.14 Hydraulic systems filter locations

Position or type	Degree of filtration (μm)	Remarks
Suction line	100–150	Must have low flow resistance to prevent pump cavitation.
Main pressure line	Down to 15 as required	High strength elements and high pressure case required. Can be bypassed for cold starts.
Individual pressure lines (point-of-use filters)	Down to 5 if required, but under 25	Gives maximum protection to individual components. Normally specified for chip control only to avoid high pressure drops.
Return line	Down to 3	High strength case not required. Usually specified for silt control.
Breathers	Down to 25 if required	Fitted to reservoir or tank to eliminate ingestion of airborne contaminants.
Bypass filter (separate loop)	Down to 25	Can be employed during a run-in period to assist in removal of ingested external contaminants; also for routine oil cleaning.
Magnetic plug	Ferrous particles only	Can be fitted in reservoir, particularly useful during run-in period.
Batch filter	Down to 5 if required	Used for cleaning and reclaiming old oil in a system. May also be used to prefilter raw oil from storage.

- hardening or embrittlement of the filter element, which can cause cracking and breakdown of the material, and
- disintegration of the element.

In general, glass microfibres, wire mesh and woven wire cloth are fully compatible with all hydraulic fluids (provided the complete filter does not include parts in aluminium, cadmium, magnesium or zinc, which are attacked by water-in-oil fluids). Cellulosic media tend to swell in water and are not generally suitable for water-in-oil and water-glycol fluids. Filters with active media cannot be employed, as these are capable of removing additives that are commonly used in hydraulic oils. Compatibility with other system components needs little comment other than that the filter should be readily fitted and coupled to existing units, and the fact that filters of the required size should be available to fit standard line sizes, etc. It is also desirable that the form of the filter is such that it is readily accessible for removal of the element for cleaning or element replacement.

Selection procedure

The following procedure could be useful when selecting filters for a given hydraulic system application – the preliminary steps are:

1. identify components that are sensitive to contamination
2. identify possible points of particle ingression and water generation

3. decide the best position of the filters (this is dependent on cost and various features of the application, such as pressure line, return line, off-line or suction line).

The detailed selection process is then:

1. estimate the ingression of particles, as a rate per minute, for the particular operating environment (Ri)
2. estimate the generation of particles, as a rate per minute, from components (Rg)
3. determine the acceptable contamination levels for system and components (Nd)
4. determine the initial level of contamination in the system (Ni) (this will depend to some extent on the cleanliness levels achieved by component suppliers; large users are in a better position to specify cleanliness levels with which the supplier must comply; system contamination is probably removed during commissioning)
5. determine the flow rates where any filters are to be fitted (Q)
6. calculate the total circulating volume of the system (this will determine the mean level of particle density and the time for cleaning during commissioning)
7. calculate the β_{10} value: for multipass flow, the formula is:

$$N_d = N_i/(\beta_{10} - 1)$$

where

$$N_i = (R_i + R_g)/Q$$

8. select a filter element from catalogues having at least this β_{10} value
9. check the particle distribution leaving the filter
10. select the element having the appropriate flow capacity (this is determined by the pressure drop arising from the flow Q passing through the filter):
11. calculate the number of particles retained by the filter per minute ($N_i - N_d$)
12. convert the number of particles retained into weight of contaminants (mg/min) retained
13. calculate the effective size of filter in terms of its dirt-holding capacity
14. increase the life of the filter if its life span is unacceptable.

This selection procedure should first be undertaken for the main filter responsible for protecting the system. Filters for protecting other parts of the system, requiring lower particle concentrations could then be selected, taking into account the filtration process produced by the main filter.

The rating of a line-mounted filter must be individually tailored to the system concerned and attention must be paid to the relative sensitivity of the components to contamination, the operating pressure and the severity of the duty cycle. It is always advisable to verify the choice of filter with both filter and component manufacturer, as they have the knowledge and experience to ensure that a correct selection is made.

Filter pressure drop

Pressure drop is related to the form and type of element chosen (that is the element permeability), but in practice is more dependent on the design and size of the complete filter rather than on media characteristics alone. For any given type and size of filter, pressure drop characteristics can be evaluated from manufacturer's data, which are, of course, directly applicable only to new elements. The corresponding K factor, found from these data, should be such – related to pressure drop by

$$P = KQ\nu$$

for filters for high pressure hydraulics, as to give not more than 1 bar pressure drop at maximum rated flow with a specific fluid. In the absence of other data, performance can be estimated fairly accurately for other flow rates, or for other fluids, from the basic formula. Similarly, approximations for the performance of other sizes of the same design of filter can be derived from the standard relationships. The variation of K with time or contaminant build-up cannot be determined other than by practical tests.

The basic formula also indicates that the pressure drop will vary with fluid viscosity (ν), i.e. with fluid working temperature. Performance figures quoted for a given viscosity can be corrected for other viscosities by the same formula. Typical allowable values for pressure drops are given in Table 5.15.

Table 5.15 Acceptable pressure drop values

Pressure drop bar	Initial	Final (dirty)
Pressure line	0.7–1.4	5
Return line	0.35–0.5	2
Suction line	0.05	0.2

Selection based on system parameters

A method has been devised to assess the filtration requirements for a given hydraulic application, based on the selection from a set of weighting factors. The method involves careful consideration of the individual operating parameters of the system, and selection of the set that defines the system concerned, for which a weighting will be given. From the whole list of parameters a total weighting will be obtained and this is then used to determine the absolute rating of the most suitable filter. This rating should, obviously, only be considered as an approximation, because of the difficulty of defining precisely the operating parameters of the system concerned.

The process involves choosing operating pressure and duty cycle, taking into account the normal operating pressure and its pattern of change, both in magnitude and frequency. The severity of the operating pressure duty is selected from:

- light: continuous operation at rated pressure or lower
- medium: medium pressure changes up to rated pressure
- heavy: zero to full pressure variations
- severe: zero to full pressure variations, with transients at high frequency (0.6 Hz) e.g. a power pack supplying a punching machine.

The next stage is to select the various weightings from Tables 5.16 to 5.22, with the pressure severity chosen above fed into the first of these tables. Finally, the total weighting is determined by adding the seven individual weightings derived from these tables. The appropriate filter rating is then obtained from Figure 5.38, which shows the relationship between filter rating and system parameters as determined by the total weighting.

Table 5.16 Pressure and duty weighting

	Duty			
Pressure (bar)	Light	Medium	Heavy	Severe
0–70	1	2	3	4
70–150	1	3	4	5
150–250	2	3	4	6
250–350	3	5	6	7
350+	4	6	7	8

Table 5.17 Environment weighting

Examples		Weighting
Good	Clean areas, laboratories	0
Average	General machining shops, lifts	1
Poor	Mobile plant	2
Hostile	Foundries, also where imgression of contaminants is expected, e.g. component test rigs	3

Table 5.18 Component sensitivity weighting

Examples		Weighting
Extra high	High performance servo valves	8
High	Industrial servo valves	6
Above average	Piston pumps, proportion valves, compensated flow controls	4
Average	Vane pumps, spool valves	3
Below average	Gear pumps, manual and poppet valves	2
Minimal	Ram pumps	1

This whole process can be well demonstrated by using a practical example: that of a large hydraulic excavator (10 m^3) operating in a quarry. The hydraulic system includes pressure compensated piston pumps and very large lift cylinders.

The system operates at 250 bar, with extremes of both flow and pressure fluctuations in a cycle that is repeated approximately four times every minute. For this reason it is considered to be a heavy duty, with a weighting factor of 4.

Table 5.19 Life expectancy weighting

Life expectancy (h)	Weighting
0–1000	0
1000–5000	1
5000–10,000	2
10,000–20,000	3
20,000+	5

Table 5.20 Component economic liability weighting

Examples		Weighting
Very high	Large piston pumps, large high torque, low speed motors	4
High	Cylinders, servo valves, piston pumps	3
Average	Line-mounted valves	2
Low	Gasket-mounted valves, inexpensive cartridge pumps and gear pumps	1

Table 5.21 Operational economic liability weighting

Examples		Weighting
Very high	Very expensive downtime, e.g. certain steel mill equipment	5
High	High volume production plant	3
Average	Mobile installations	2
Low	Equipment not critical to production	1

Table 5.22 Safety liability weighting

Examples		Weighting
High	Mine winding gear braking systems	3
Average	Where failure is likely to cause a hazard	1
Low	Some hydraulic component test rigs	0

The environment in which this machine is working can, in dry weather, be very dirty and ingression, both airborne and maintenance-induced, is likely to be high, hence its weighting is 2.

Although the majority of the components are to be of average commercial quality, the pumps are of above average sensitivity, hence the weighting is 4.

The annual usage is about 2000 hours and component life is expected to be about 4 years – a life expectancy of 8000 hours, with a weighting of 2.

Some components, such as lift cylinders and variable piston pumps, are quite expensive for the end-user to purchase (e.g. lift cylinders can cost up to £15,000), therefore the component costs are taken as high, hence the weighting is 3.

Economic liabilities caused by downtime vary depending upon the specific quarry situation, but the high capital cost of the system puts it in the high operational liability category, with a weighting of 3.

No additional waiting for safety is required.

Therefore the total weighting, equal to the sum of the individual weightings, is 18. This figure, referred to in Figure 5.38, shows an absolute filter rating in the range of 4–13 μm.

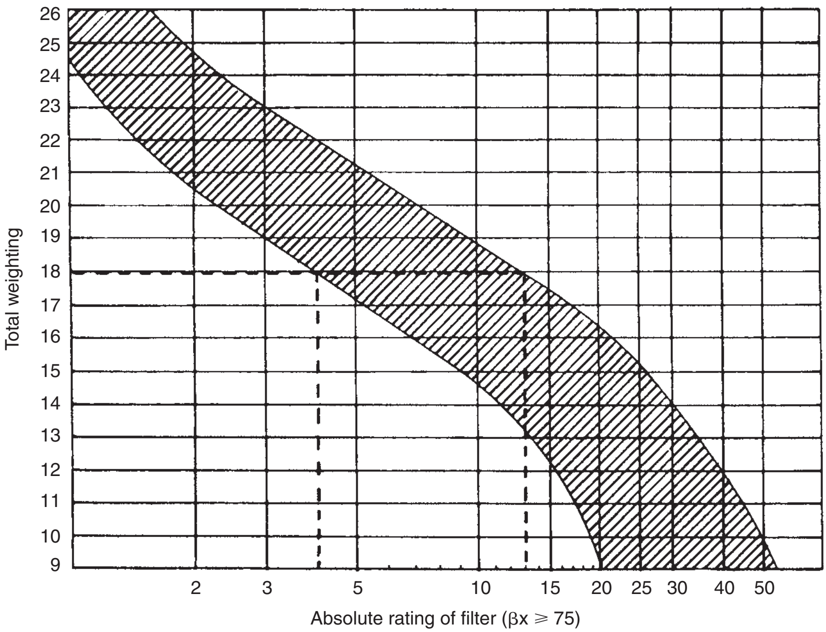


Figure 5.38 Filter rating determination

Flow rate

In the selection of a filter, the maximum flow rate and maximum acceptable pressure drop for the system must be known, as these will affect the element size required. The minimum requirement is that the filter should be sized to handle the maximum flow rate possible from the pump.

Filter size

Filter weight is generally a less significant factor, although here it can be noted that filters with recleanable elements are usually heavier and bulkier than their disposable element counterparts. Excessive size (or weight) could inhibit the use of a line filter at a point where it would be most effective. Also, with the more expensive types of element, a reduction in size represents a direct reduction in cost. Equally, the availability of small compact filters for in-line duties favours their use for individual component protection, where they can be more effective than a single system filter.

Pressure surges

The subject of high pressure surges needs further comment. Certain media, whilst possessing excellent filtering properties, have low strength when wetted, and can burst under high differential pressures, or become displaced, allowing the fluid to bypass the element. Multiple layer construction can usually guard against such failures, but permanent damage to a filter element can result. The solution is not always a matter of filter design or type. Thus, if peak pressures of 700 bar are realized in a 14 bar system (not an uncommon situation), the employment of a filter with a pressure rating of five times the normal maximum differential pressure is not necessarily a logical or practical answer. A better solution in such cases may be to investigate the system design as a whole, relocating the filter in a more favourable position, and possibly applying surge-damping to the system.

Cost

Cost is an indeterminate factor. In general, the finer the degree of protection provided, the higher the cost of the filter, but the overall savings in terms of reduction in wear and increased reliability of service can be very real. Because filters are such unobtrusive components, their importance is often underrated and the designer should err on the side of over-protection rather than under-protection (or purely nominal protection), unless this is quite inconsistent with the system economics or performance requirements. For example, the finer the degree of filtration required, the shorter the time that should be allowed between element cleanings, unless an extra large size of filter is fitted. Where system maintenance receives scant attention, a bypass may be fitted to the fine filter, with the distinct possibility that the system will continue to be operated for a considerable period with the filter ineffective. The advantages of employing fine filtration initially are then destroyed.

Protective devices

Filter housings commonly incorporate protective devices, such as shut-off valves, check valves, reverse-flow valves and a bypass facility. Shut-off valves are usually incorporated in the filter head, automatically sealing the outlet and inlet lines when the filter housing is removed (for example, to replace an element). They also have the advantage of minimizing air entrainment during replacement of the filter element. It should be noted that shut-off valves, where fitted, are normally effective only at low system pressures (that is, not full system pressure unless specifically stated).

Check valves may be fitted to inlet and outlet ports to prevent reverse flow occurring through the filter.

Reverse-flow valves may be fitted to provide a bypass loop in the event of reverse-flow conditions, and thus eliminate any back-pressure on the element. With some elements reverse flow can result in damage.

Bypass housings incorporate a bypass valve, which opens at a predetermined differential pressure across the filter element. Flow is then directed partially through the filter element and partially through the bypass. In the event of the filter's becoming fully clogged, flow is maintained through the bypass. Significant parameters for the system are the opening or cracking pressure of the bypass valve, its resealing pressure (typically 60 to 75% of the cracking pressure), and the maximum obtainable pressure drop through the bypass at rated flow.

A filter with a bypass housing only provides complete protection for the hydraulic system when the bypass is closed, as in normal use. A non-bypass housing is essential when all the fluid must be filtered all the time. In this case the onset of clogging, causing an increase in differential pressure to a predetermined level, can trigger a visual and/or audible alarm, via a pressure switch, or similar device.

Calculation model

A filter model can be developed, to permit system definition, by choosing a point in the system and writing an equation for the contaminant particles entering and leaving that point. It will be appreciated that different locations of the filter require different system models. Thus, a suction line filter removes contaminants before they enter the pump. Since the reservoir then collects all generated and ingested contaminants, it can be considered as the contaminant ingestion point for the circuit. On the other hand, a pressure line filter removes contaminant either between the pump and the other components, or between any of the components. The ingestion point is thus either between pump and filter, or at the reservoir.

A bypass circuit allows a large portion of the total pump flow to bypass the filter. In such a circuit, the filter handles only the amount of flow necessary to maintain the contamination level required by the system components. This lower flow specification allows the use of a smaller, less costly filter, but can still provide maximum component life. In the bypass circuit, the ingestion point can be after the work components, but before the bypass line, or at the reservoir.

For the appropriate filter site, equations can be written about these points of reference for the changes in contaminant particle content at that point. The equations are computer soluble, and show that no filter will remove 100% of contained and ingested particles. Rather does the system eventually reach an equilibrium where contaminated concentration remains constant. If this concentration is below the sensitivity levels of the most sensitive component, system life will be satisfactory.

Filter cost generally increases with increasing size and increasing β ratio, with size having more effect. Since suction and pressure line filters must handle higher pressure flows, these installations may require larger, more expensive filters. Return line and bypass filters, on the other hand, operate at lower pressure and are usually less expensive.

Systems management

The purpose of systems management is to achieve the most economic cost over the life cycle of any system. This is not the same as achieving maximum reliability, neither is it the lowest possible cost of purchase. Several aspects must be borne in mind and an overall assessment made. In any system, hydraulic or otherwise, total lifecycle cost can be considered under the following headings:

1. specification
2. procurement
3. installation
4. commissioning
5. operation
6. maintenance
7. replacement
8. disposal
9. training of personnel.

Specification

In defining specification, the work programme of the system must be described (including its environment and any other factors that might affect the reliability). In addition, some indication must be given as to the life or reliability that is required and how this could be achieved, such as by using high grade components or a specified maintenance programme.

It is possible that the specification is not adequately proven. It may be completely new and, therefore, it may make economic sense to have a computer-aided performance simulation undertaken. Alternatively, special trials may have to be included in the program.

Procurement

Depending on the facilities available (and costs), obtaining the system may either be by straight purchase from a manufacturer or supplier, or it may entail detailed design and manufacture. Either way the level of cleanliness of components must be specified and achieved. The packing, delivery and storage of the items must be carefully controlled, so that additional contamination does not enter before the system is built.

Installation

It is important that an inspection be undertaken at the installation stage. Incorrect build can cause adverse effects, which may not be easily removed and ultimately will reduce the life of the system. A check must be made on both the components and the pipework as supplied and in the process of connecting up the system. Flushing of the system before use cannot be overemphasized.

Commissioning

This is more than just checking that the system provides the correct work programme. A check should be made on the monitoring equipment to see that it has been fitted and is working. It may be sensible to include a defined fault in the system to see if the alarm signal works or the close down operates as it should.

Operation

The costs of operating the system are not directly related to reliability. If the system is working correctly then it has a specific cost anyway. However, it may be of value to calculate the losses that would be incurred should the system breakdown, such as loss of production, or penalties for delays in delivery.

Maintenance

Proper maintenance keeps an eye on the health of the system. Some is preventative maintenance in the sense of applying routine examination and replacement at specified times, such as oil changes, filter changes, etc. Other is corrective maintenance where perhaps an automatic monitor has signalled the closeness of distress, such as by the temperature of the fluid.

A good procedure is to record trends where transducers are fitted, so that when the operation is repeated, early warning of impending failure will become obvious. Items that can be logged in this way could include fluid temperature, system pressure, filter differential pressure, fluid level, fluid condition and contamination class of the fluid. Whilst making a log, a section could be devoted to general observation of noise or leakage, smell or response.

Replacement

The cost of replacement varies according to the cost of obtaining spares, storing spares, ease of refitting, downtime lost, etc. Monitoring transducers should be more reliable than the system they are monitoring, but some estimate of their replacement cost should also be made.

Disposal

Disposal is not normally a heavy expense for hydraulic systems and monitoring devices. There are some instruments that are radioactive, with thin layer activation, but not a serious level.

Training of personnel

Several of the previously mentioned aspects require definite training of personnel. In particular, it is necessary to impart an awareness of the problems of contamination. The use and misuse of the various transducers should be included, rather than just a passing on of an instruction sheet. It is good practice for the maintenance personnel to be included in the commissioning stage: they will sense their position as part of the total team, and will value the extra training given.

For optimum economic reliability and system life, a planned systems management programme is essential. Because costs relate to the whole life of a system, a true perspective can only be achieved by considering the costs throughout the life cycle.

6

GAS FILTRATION

SECTION CONTENTS

6A. INTRODUCTION

The investment in gas filtration of all kinds is about one sixth (16%) of the total investment in filtration and its related separations, world wide. This makes it an important component of the filtration business, and, considering how vital some applications are to the quality of the air breathed in by people and machines, its qualitative importance is greater still.

This section of the Handbook covers all aspects of the filtration of air and other gases: inlets and outlets, hot and cold, working and living spaces, machinery and respiratory. It deals with air as a working medium, as in pneumatic systems, and with the recovery of dust from process and engine exhausts.

In almost all applications, the demand for fine filtration is strong, and getting stronger. Human realization of the importance of the quality of the atmospheric environment is growing, and air quality standards are much higher than they were 50 years ago. Filtration is the process that is primarily responsible for these higher standards, and this Section is almost entirely concerned with filtration applications, although mention is made of one or two non-filtration methods of gas cleaning. The motor-driven centrifuge, however, has no part to play.

A significant feature of most gas filtration is the relatively low concentration of contaminants in the inlet air, coupled very often with a high gas feed flow rate. The function of most gas filters is therefore a clarification one, for which the management of the collected dust is not a major concern – except, of course, for the filters used as exhaust stream dust collectors.

6B. INDOOR AIR QUALITY

Probably the largest number of air filters is found in the systems controlling the quality of the air in living accommodation (domestic, commercial and institutional) and in working spaces, especially the growing number of clean room installations for critical assembly processes. These are now being supplemented by the vent filters controlling discharges from working spaces in which potentially hazardous atmospheres are used.

Conveniently grouped under the term ‘air conditioning’ (or within the acronym HVAC), these filters are the basic means whereby improvement is achieved in the indoor air quality (IAQ) within which humans live or work. It is now believed that ‘sick building’ syndrome, a condition that causes people to feel sick inside a certain building only to recover on leaving it, is an air-conditioning problem, likely to be cured by better filtration.

This section looks at both the filters that are used for air cleaning, i.e. filtration of air free from fairly low levels of contamination, and the systems in which these filters are used. Figure 6.1 gives a view of the sizes of many of the common air contaminants.

Filters designed for the treatment of air fall broadly into three categories:

- primary filters, designed to trap the majority of larger airborne dust particles of 5–10 μm in size, have high dust-holding capacity; these are usually of the dry panel type or roll filters, capable of working with relatively high airflow velocities
- second-stage filters, with finer media for trapping and retaining finer particles passed by the primary filter, such as particles of 5 μm diameter and smaller; these smaller particles (0.5–5 μm) are the most damaging as regards staining of decor in buildings, harmful effects on machinery and in pressure equipment and so on; these filters may be of the unit or panel, pocket or bag type, with extended depth of filtration; maximum air velocities are generally low, of the order of 0.12 m/s or less
- ultra-fine, or final stage filters, yielding very high efficiencies (99.95% or better) even with sub-micrometre particles; the chief types here being the high efficiency particulate air (HEPA) and ultra low penetration air (ULPA) filters, employing a high density medium built up from synthetic spun fibres with a sub-micrometre diameter and made in the form of a closely pleated pack; air velocity in this case is limited to about 0.03 m/s.

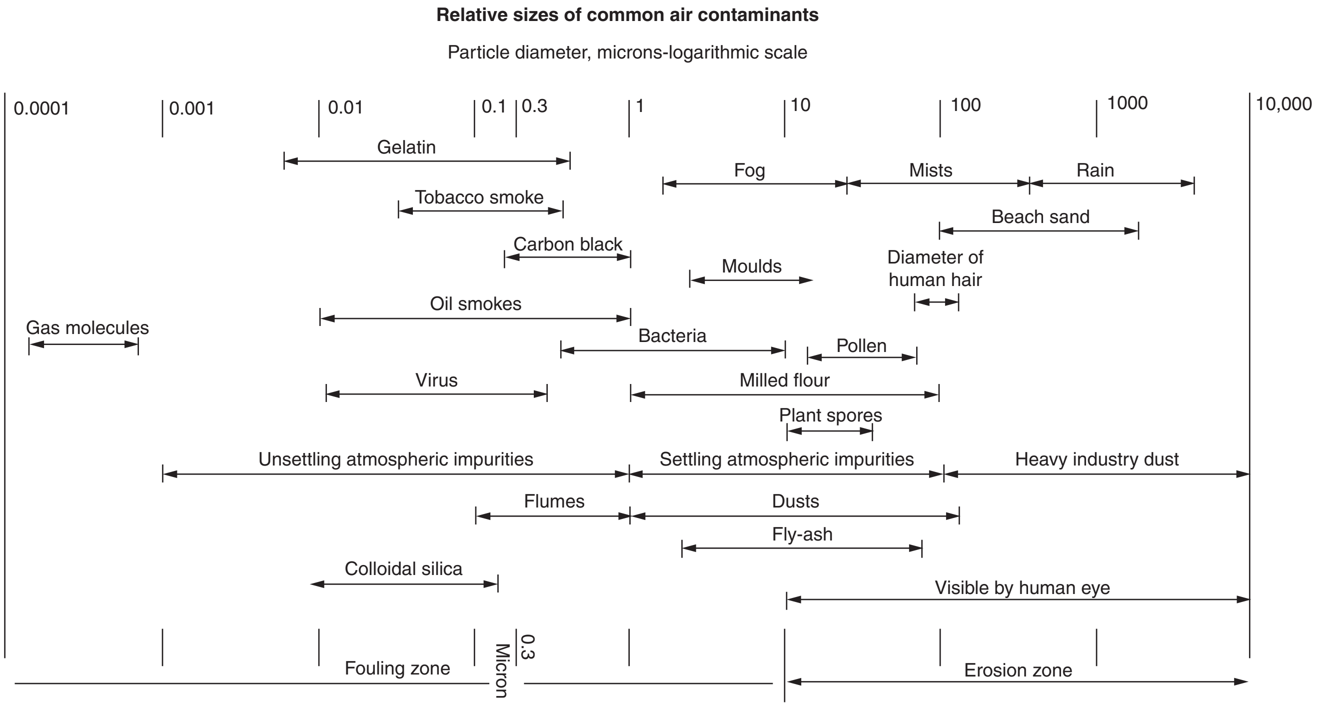


Figure 6.1 Common air contaminants

Electrostatic precipitators also come into this last category because of their capacity for ultra-fine dust filtration, although they can operate with much higher air velocities.

A single-stage system using a low or medium efficiency filter has the lowest capital cost but, as stated, will not filter very fine contaminants. A multi-stage system will filter virtually all atmospheric pollution but at higher capital investment. The filter cost itself will be low, because the cheaper primary filters prolong the life of, and protect, the more expensive filters.

However, attention must be paid to the consequences of installing inadequate air handling filters thereby allowing fine particles to enter the air handling system. Over a period of time, airborne contaminants will build up in the system to create a potential hazard. As much as correct filter selection is very important, equally important is proper system maintenance. Clogged filters impede airflow and damaged filters contribute to a loss of efficiency, ultimately damaging the air handling and distribution equipment, allowing dust and pollutants to circulate. A multi-stage filter system as shown in Figure 6.2 will guarantee clean air, so long as it is kept in good order.

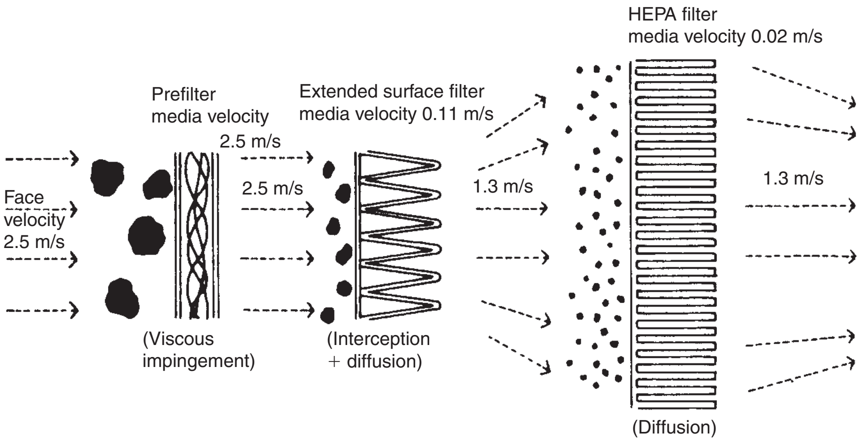


Figure 6.2 Multi-stage filter system

Air filters and other types of air cleaning equipment can be grouped together as follows:

- cartridge filters – mainly used as engine intake filters and filters for compressed air systems
- pad filters – disposable elements made from flat pads of thick fibrous material mounted in frames or panels
- panel filters – unit filters (including pads) of various media forms, which may be disposable (e.g. by using synthetic fibre or spun glass media), washable (by

using polyurethane foam or a similar material), cleanable (e.g. woven metal wire mesh cleaned by immersion in an oil bath) and non-combustible

- viscous panel filters – employing screens or media wetted with oil, or dry fibre coated with an adhesive gel
- roll filters – which are basically panel filters with the filter medium automatically fed through the panel frame from a clean roll on one side to a dusty roll on the other
- rotating viscous panel filters – in the form of a continuous curtain loop of metal slats or something like it, automatically rotated across the frame, and passing through an oil bath (the oil acting both as a viscous impingement collector and as a cleaning agent)
- bag or pocket filters – normally arranged as a group across the panel frame and extending through the dividing wall, to provide high efficiency filtration with high dust retention
- particulate air filters (HEPA and ULPA) for final stage filtering
- electrostatic precipitators – which may be of the dry type (agglomerators), or have the plates periodically cleaned by water washing (in the dry type, the dust is collected in filter bags or a separate downstream filter)
- louvres – an aerodynamic type of separator, which also has a capacity for collecting liquid mist particles
- separators – various types of equipment, working on aerodynamic principles, and
- scrubbers – wet or dry dust separators using liquid sprays or packed beds of granular solids.

Air filter classification

Air filters are classified according to their filtration efficiency, when measured under defined standard conditions. There is no single international standard for such classification, but there are a few national and regional standards that have been brought together by CEN (Comité Europèen des Normalisations) and EUROVENT (European Committee of Air Handling & Refrigerating Equipment Manufacturers), as well as in the United States by ASHRAE (American Society of Heating, Refrigerating and Air-conditioning Engineers). Table 6.1 shows the EUROVENT and CEN classifications for ventilation filters, and Table 6.2 the very similar form of the ASHRAE 52.2 classification.

These classifications are considered to be a proven method for designing air filtration media according to average synthetic dust weight arrestance and average dust spot efficiency, although it should be stated that the whole test situation is complicated by not only the diverse test procedure but the diversity of particulate materials specified for them.

Glass fibre media used to be favoured because they were produced with a graduated matrix to provide very high dust retention capacities. However, due to the possibility of element migration (the more likely with chopped strands than with continuous filaments), the trend is now towards the use of non-breaking, non-shedding

Table 6.1 CEN/EUROVENT classification

Type	Eurovent class	CEN EN779 class	Efficiency (%)	Measured by	Standards
Coarse dust filter	EU1	G1	<65	Synthetic dust weight arrestance	ASHRAE 52–76
	EU2	G2	$65<80$		
	EU3	G3	$80<90$		Eurovent 4/5
	EU4	G4	>90		
Fine dust filter	EU5	F5	$40<60$	Atmospheric dust spot efficiency	BS 6540
	EU6	F6	$60<80$		
	EU7	F7	$80<90$		DIN 24 185
	EU8	F8	$90<95$		
	EU9	F9	>95		EN 779
High efficiency particulate air filter (HEPA)	EU10	H10	85	Sodium chloride or liquid aerosol	BS 3928
	EU11	H11	95		Eurovent 4/5
	EU12	H12	99.5		DIN 24 184
	EU13	H13	99.95		(DIN 24 183)
	EU14	H14	99.995		
Ultra low penetration air filter (ULPA)	EU15	U15	99.9995	Liquid aerosol	DIN 24 184
	EU16	U16	99.99995		(DIN 24 183)
	EU17	U17	99.999995		

Table 6.2 ASHRAE 52.2 classification

Category	Class	Minimum Efficiency % at Size Range, μm			Std 52.1 Arrestance %	Final Pressure Pa
		0.30–1.14 μm	1.14–3.46 μm	3.46–10.0 μm		
Coarse	C1	–	–	$E_{min}<20$	$A_{avg}<65$	150
	C2	–	–	$E_{min}<20$	$65\leq A_{avg}<70$	150
	C3	–	–	$E_{min}<20$	$70\leq A_{avg}<75$	150
	C4	–	–	$E_{min}<20$	$75\leq A_{avg}$	150
Low Eff	L5	–	–	$20\leq E_{min}<30$	–	150
	L6	–	–	$30\leq E_{min}<45$	–	150
	L7	–	–	$45\leq E_{min}<65$	–	150
	L8	–	–	$65\leq E_{min}<80$	–	150
Medium Eff	M9	–	$E_{min}<30$	$80\leq E_{min}$	–	250
	M10	–	$30\leq E_{min}<45$	$80\leq E_{min}$	–	250
	M11	–	$45\leq E_{min}<65$	$80\leq E_{min}$	–	250
	M12	–	$65\leq E_{min}<90$	$80\leq E_{min}$	–	250
High Eff	H13	$E_{min}<65$	$90\leq E_{min}$	$90\leq E_{min}$	–	350
	H14	$65\leq E_{min}<80$	$90\leq E_{min}$	$90\leq E_{min}$	–	350
	H15	$85\leq E_{min}<95$	$90\leq E_{min}$	$90\leq E_{min}$	–	350
	H16	$95\leq E_{min}$	$95\leq E_{min}$	$95\leq E_{min}$	–	350

synthetic organic fibres. Synthetic air filter media are progressively structured, high in density and performance, nonwovens, made from synthetic fibres, usually thermally bonded, or resin bonded, with an adhesive coating in full depth on each individual fibre.

Synthetic fibre air filter media can be used in most atmospheric air or recirculated air filtration applications, and are particularly suited for the ventilation of offices, factories and public buildings, for air handling in hospitals, computer rooms, schools, airports, pharmaceutical and food processing plants, clean rooms and laboratories.

Air filter selection

Air filter units should be selected on the basis of the following items:

- level of filtration needed
- filter classification requirements
- cost-effectiveness
- stable collection efficiency, and
- dust storage capability at a low pressure differential level.

Particular points to be borne in mind during the selection process are:

- the air flow should be as uniform as possible across the face of the filter
- prefilters should be used with high efficiency filters to give longer service life
- if the system draws in air from an external wall, then weather louvres and bird screens should be fitted at the intakes
- a differential pressure drop gauge should be fitted across the system to determine when a filter should be serviced
- sufficient access should be provided for servicing the filters
- filters should not be used beyond their specifications
- the recommended final resistance should not be exceeded
- electrostatic air cleaners should not be installed where free moisture can affect them
- the selection of air filters on the basis of lowest cost is not a reliable option in any system design, future needs should be borne in mind, and
- system requirements should be fully discussed with equipment manufacturers.

Pad and panel filters

By far the largest number of ventilation filters is of the flat panel type, square or rectangular in shape, and of a standard size to be accepted as a push fit into appropriately sized spaces in the dividing wall separating the ventilated area from the outside atmosphere. The simplest form has a flat panel of thick, depth filtration medium (Figure 6.3) held in a cardboard or thin metal frame. This pad filter has a relatively low surface area available for filtration.

More commonly, the filter medium is pleated and/or corrugated, with pleats of different thickness, held within the same kind of frame as the pad (Figure 6.4), but now, because of the pleating, providing a much larger filtration area.

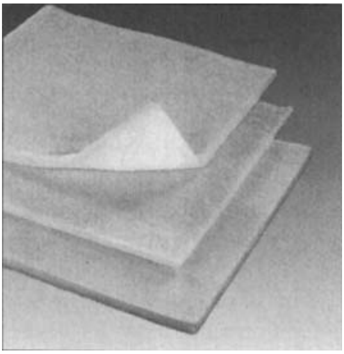


Figure 6.3 Filter pad media

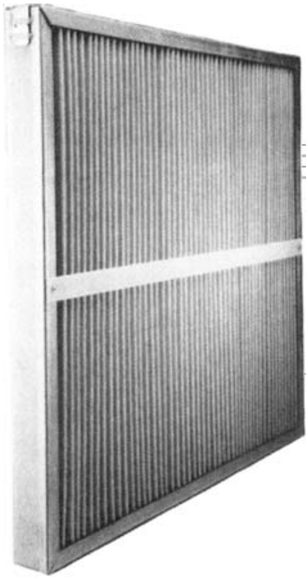


Figure 6.4 Pleated filter panel

While the filter medium is protected on both sides by some stronger material, such as wire mesh, before it is pleated, the pack of pleats is further protected from distortion within its frame by retaining screens (see Figure 3.38).

These simple screens and filters can be classified under three headings, depending on whether or not the element is reusable. Thus, in the case of elements that cannot be cleaned, the complete panel is removed for disposal, and replaced with a new one, when the pressure drop across the panel has risen to an unacceptable level. Other panels may be designed with semi-permanent elements, whose cleaning can be accomplished by removing the panel, laying it face downwards and tapping it gently to remove the dust (or possibly the dust may be removed with a vacuum cleaner). The number of cleaning cycles that can be achieved without damaging the element is limited, hence the type is referred to as a semi-permanent panel.

Permanent panels have stronger elements, which are readily cleanable by removal and washing. These may be dry filters or viscous panel filters, employing metallic elements with or without fibrous interlayers. A particular advantage with viscous panel filters is that they can be designed to have constant or even reducing efficiency characteristics with time, so that the pressure drop will not rise excessively even if cleaning of the filter is delayed or neglected.

Various media, woven and nonwoven fabrics, paper, wire mesh and even membranes may be employed for dry panel filters. The most favoured materials are synthetic fibres and glass fibre, in a pad or mat, in multi-layer or pleated form. It is becoming increasingly common practice to coat the media with a viscous agent to ensure high dust retention.

Fully cleanable (permanent) filters normally employ elements formed from woven wire mesh or metal fibre mats, which may be reinforced with wires or layers of corrugated expanded metal, the whole being assembled in a metal frame for durability. Characteristics vary widely with the actual form of element construction employed, and so direct comparisons cannot easily be drawn with other types.

Viscous panel filters

Viscous panel filters provide dust retention by the effective impingement of dust on a large area of oily surface. In this respect they can have a superior performance to dry filters (particularly in heavily contaminated atmospheres). Their effectiveness, however, will also rely on adequate particle retention properties to eliminate subsequent re-entrainment of particles as the oil is dried up by collected solids. In practice, the retention properties can be adjusted to give constant efficiency or falling (reducing) efficiency.

This is controlled by the operating characteristics of the viscous panel. If wetting characteristics are adequately maintained, efficiency remains high and substantially constant. In certain circumstances, efficiency may increase, as with conventional dry filters, if the presence of oil on the element assists the formation of a porous bed of solids. If the degree of wetting decreases markedly with build-up of contaminants, the retention properties of the filter will fall, hence its efficiency will also fall.

A simple viscous panel filter comprises one or more layers of wire mesh, usually in crimped or deeply pleated form, or even wire wool held between two layers of mesh. Such types generally tend to have relatively low efficiency and only moderate retention properties. They may also be subject to channelling, where the airflow is directed through individual paths, rather than being distributed over the whole filter area. Better performance is usually achieved by sandwiching a layer of cotton gauze or similar absorbent medium between layers of wire mesh, the gauze both decreasing the average air passage dimension, for increased filtering efficiency, and also increasing the effective mass of oil that can be retained by the panel (i.e. increasing the degree of wetting).

Viscous panel elements incorporating absorbent media layers will normally have constant (or even increasing) efficiency characteristics. Reducing efficiency characteristics are usually given by all-metal construction. Here, efficiency is high as long as the wire surfaces remain tacky, but as the oil is absorbed by accumulating dust, retention capacity falls. This can be advantageous in applications where it is more important that lack of attention to filter cleaning does not generate excessively high back pressure, than the fact that high filtering efficiency is always maintained. On the other hand, with regular cleaning and rewetting at suitable intervals, the performance of a reducing efficiency filter can remain high in service.

Panel filters constructed from multiple layers of expanded aluminium foil or stainless steel mesh (as shown in Figure 6.5) are often used for grease filtration, mist removal and particulate filtration. The units are generally fitted above grills and cookers in commercial and domestic kitchens. The panels have a low initial resistance to air flow and can be installed in high humidity environments, in heating, ventilating and air-conditioning systems, hot air heating units, and for the removal of particles from gas flows in industrial processing. For particulate removal applications, each layer of expanded aluminium foil or stainless steel mesh is usually precoated with a thixotropic filter coating adhesive.

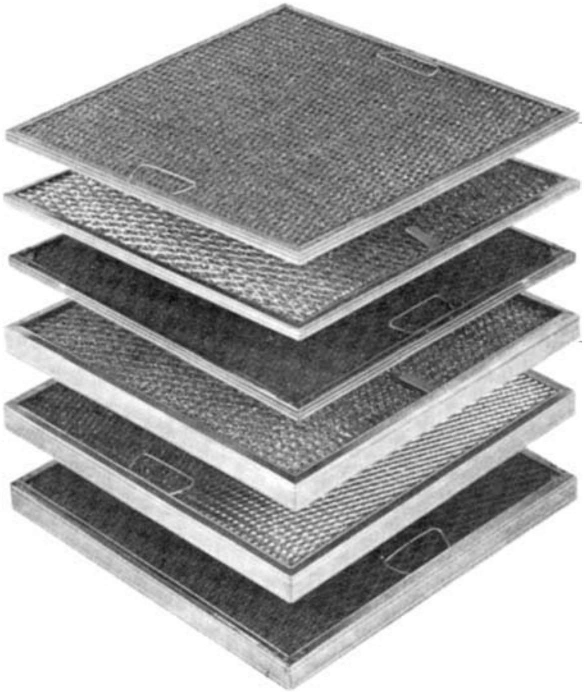


Figure 6.5 Expanded metal panels

Activated carbon filters

Activated carbon filters are intended for the removal of fumes and odours from gases, with particulate removal as an incidental activity. Some of the most common applications for the treatment of airborne noxious fumes and gases are in areas such as office blocks, airports, hospitals, and theatres. They are also used for the removal of solvent vapours, toxic contaminants or other odours, which can cause offence in a variety of industrial, chemical and commercial environments. For use in air-conditioning applications, the activated carbon is held in a panel, of the same shape and size as a filter panel (Figure 6.6), in which the carbon granules are immobilized: bonded at their contact points to form a 'biscuit' and encased in a metal frame (which, in turn, is usually located with a number of other filter panels in a housing). These housings can be designed for front or side withdrawal of the panels, with prefilters to protect the activated carbon panel filters.

Figure 6.6 Activated carbon panels

Loosely filled granulated activated carbon is better suited to large deep-bed filters, which often require media depths of up to 1 m. Low depth, loosely filled filters can prove less effective due to their tendency to settle and allow the air to bypass the activated carbon medium or for the activated carbon itself to escape from the filter in the air stream and form into carbon dust. Loosely filled systems will almost always be specified for highly contaminated applications, such as some industrial processes, where deep-bed filters are required.

An important development is the growth of chemically impregnated granulated activated carbon for filtering out or neutralizing specific inorganic molecules such as sulphur dioxide, hydrogen sulphide and many others. Increasing concerns about volatile organic compounds (VOCs) in the working environment are giving carbon filters greater prominence.

Roll filters

Roll filters are normally automatic in operation. The filter medium may be a woven or nonwoven synthetic cloth, a glass fibre mat or similar material, possibly backed with mesh for additional strength or even carried on a screen. The filter medium may be treated with special wetting fluid to improve dust capacity and filtration efficiency. The cloth roll is simply spooled from top to bottom (Figure 6.7), being replaced with a new spool when the whole length has been run through. The part of the roll filter frame that holds the medium is built into the partition wall, and the incoming air is drawn through the medium. Roll filters can be mounted to move the medium vertically (as shown in Figure 6.7) or horizontally.

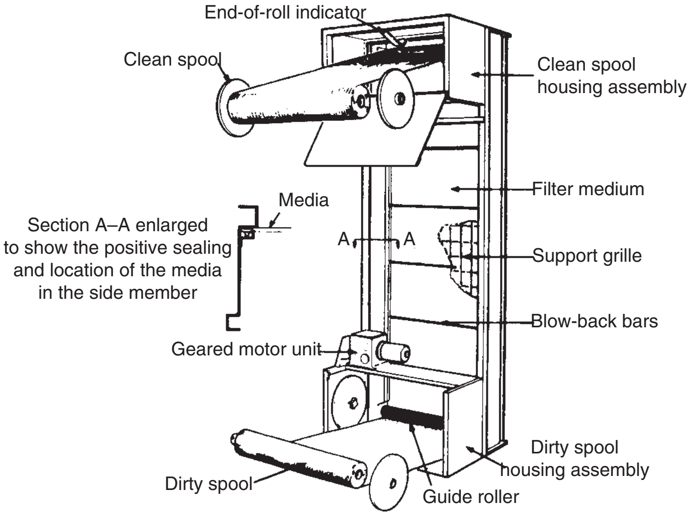


Figure 6.7 Vertical roll filter

Various forms of automatic control are possible, the most common being to actuate movement of the filter cloth by a pressure differential system. This can be preset to operate at a specific differential pressure across the filter medium and start the drive motor. The motor is then triggered-off, stopping the cloth in position when a sufficient new area is exposed to lower the differential pressure back to the original clean figure. A separate inching control is also provided for operating the filter during service, and an end-of-roll indicator to show when the upper spool is running empty.

Instead of a flat traverse, the filter cloth may run in a V-shaped path to increase the effective filter area. The units may also operate vertically face downwards, and they may, of course, also be made self-cleaning by continuous recirculation of the filter medium.

Bag and pocket filters

Bag and pocket filters, as their names imply, have their media in the form of a cylindrically shaped bag or an elliptically shaped pocket, closed at one end and open at the other. In principle, dust may be collected on the inside or outside surface, with air flow from inside out or outside in, respectively. Filter bags, for gas filtration, are mainly used in large numbers in bag houses ('fabric filters') for the filtration of solid-gas suspensions with a reasonably high solids content. They are discussed in more detail in Section 6D.

Although filter pockets can also be used singly, they are much more often found in groups of 4 to 8, mounted side by side in a rigid front member, which holds the pockets open, and from which they can be withdrawn for disposal (see Figure 3.46). This holding frame is made to the same size as the filter panels, so that the pocket panel can be clipped into the same sized space.

The pocket filters provide a much higher filter area for a given entry or panel size, than the equivalent flat panel. The pockets, which form the filter element, need to be of somewhat stronger construction than the media used in the flat panel elements, but may range from impregnated paper, through natural and synthetic fabrics, to glass cloth, depending on the application involved. For industrial applications, and where fine filtering is required, the pockets are often made from synthetic fibres, or glass wool, protected on both sides by an open mesh scrim.

Multi-layer construction is also employed using different filter media, e.g. an inner layer of rather more open form for dust retention, an intermediate layer for fine filtration and an even closer outer layer to prevent fibre migration. Synthetic fabrics are proving to have some advantages over spun glass fibre materials although glass fibre media have proven to be very efficient.

Very high filtration efficiencies are possible with filter pockets, depending on the filter medium used, e.g. up to 99.8% efficiency with DIN 24 185 test dust. Performance also depends on the pockets' remaining rigid and 'inflated', even at reduced or zero air flow. Most pockets are self-supporting by their very construction, particularly if they are mounted vertically; others require hooks, loops or wire mesh for support.

Pockets are invariably disposable rather than reusable, either individually or the whole panel, so material cost can affect the choice of pocket. Any additional cost, however, is often recoverable, since, in many applications, a pocket filter can provide its own primary and secondary stage filtration, and does not need to be preceded by a coarse primary filter.

A properly designed pocket filter can perform efficiently from 25% up to 150% of the normal air flow, i.e. it is particularly suitable for variable air volume systems. Pocket filters are available for numerous applications in many configurations, and are capable of maintaining a low pressure drop for over 8000 hours.

Pocket filters are particularly suitable for the filtration or fine filtration of atmospheric air intake and/or recirculated air in air handling installations, including ambient air handling as well as process air intake installations. Specific applications include air handling installations for the ventilation of factories, warehouses, department stores, offices, school computer rooms, public buildings, conference or exhibition halls and laboratories, as well as for cooling-air intake filtration of gas turbines, compressors and engines. They are used for prefiltration in the air intakes of paint spray booths, and before fine or very fine air filters, or HEPA or ULPA filters, or activated carbon filters.

The flat panel filter has a low surface area for filtration, which is greatly enlarged by the pleating of the filter medium. A similar increase is achieved for the pocket filter by giving the medium a pleated structure. The pleats here cannot be so deep as in thicker flat panel elements, but in the form of the V-block element (Figure 6.8) the minipleats still provide a very large filtration area, and the V-block is becoming a major part of industrial and power generation air intake filtration.

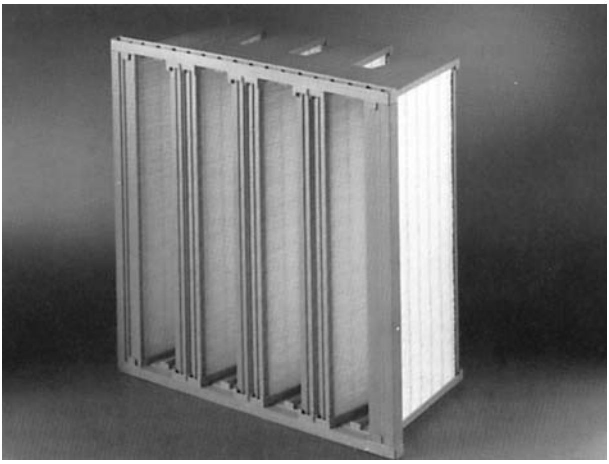


Figure 6.8 Mini-pleated V-block panel

Electrostatic precipitators

The electrostatic precipitator (ESP) cleans dusty air by imposing an electric charge on the solid particles, and then passing the suspension between some vertically hanging charged plates (electrodes). Each particle then moves towards the oppositely charged plate and, with proper design, reaches it and is held on to it.

This is not primarily a filtration process (although it is a large-scale reproduction of one of the mechanisms of filtration), and it is discussed further in Section 7. Some filters are used in an ESP installation – usually a prefilter to trap large particles, and maybe a final filter to catch any material not caught by the electrodes.

Louvres

Louvres work on the principle of inertial separation, but the aerodynamic design involved is somewhat critical. A successful example is shown in Figure 6.9, which comprises a V-shaped pocket, usually of all-welded construction. The downstream ends of the pocket are solid, with one or both sides of the V made up of the formed louvre slits. Dirty air enters the open end of the pocket, and dust is separated from the air as the air turns almost through 180°, to pass through the open louvred slits in the side of the V. The dust continues on in its original direction and is concentrated at the apex of the V. In order to allow continuous removal of the separated dust, the V apex

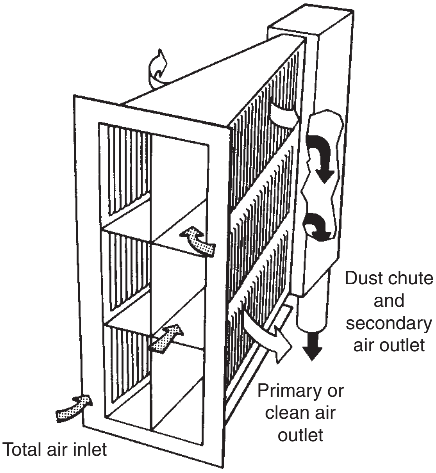


Figure 6.9 Louvre air cleaner

contains a slot along the entire length of the louvre sheet. This slot allows the separated material to enter the dust chute, which collects the discharged dust from one or more louvre sets, and conveys it to the desired point of disposal. In order to convey the separated material, a small amount of air passes through the slot as secondary air.

A louvre system like this will operate over a wide range of velocities through the louvre blades without a loss of efficiency, provided the proper relationship of secondary to primary air is maintained. Normally, the secondary air is 10% of the primary air, but this proportion can be changed to provide, within limits, desired changes in cleaning efficiency. The velocity through the louvre blades, which is used on any one installation, is determined by the allowable pressure drop across it. Thus, a dust louvre of a given area may have an infinite range of flow rate capacities as determined by the allowable pressure drop allocated to the dust louvre. The system has been used with primary air pressure drops from 0.75 to 24 cm (water gauge).

Air handling systems

Air handling systems, in which air filters play a prominent part, can be categorized as follows, by their usage for:

- building installations, from individual houses to large apartment complexes and hotels or office blocks, including heating, ventilating and air-conditioning (HVAC) systems
- industrial air filtration, including factory ventilation as well as machinery air intakes and exhausts
- clean rooms, with their very special requirements on air intake and often for venting as well, and
- moving vehicle ventilation, whether it be a private car, a coach, a train, a passenger airplane or ship.

In order to meet and comply with environmental and local health and safety controls, each air handling installation may require an individual solution. It is important to consider fully the various options and levels of filtration available to meet the performance requirements: over-engineering can be just as expensive as under-engineering.

Building installations

In building services a primary consideration of the filtration system is to achieve the optimum balance between capital cost and running costs. The latter are particularly important in times of rising costs, both as regards maintenance, labour costs and replacement of expendable filter media (disposable filter elements). The trend, too, is towards the adoption of pre-engineered package units for air handling, rather than of piecemeal installation on site. In general, this proves to be more economic and is more readily analysable in terms of likely future material costs: such figures should be available from the manufacturer of the central station unit, including fans, heat exchangers and humidifiers, in addition to the air filtration system.

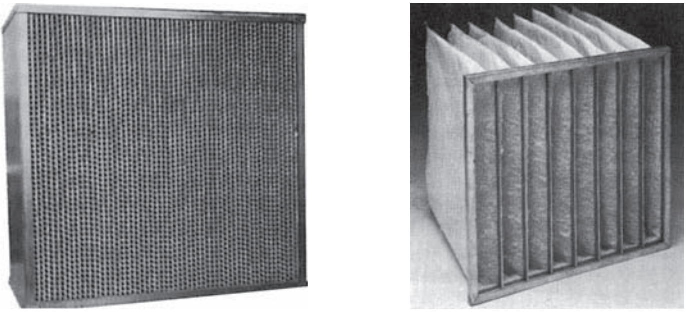
A further advantage of the package deal is that the panel filters, pocket filters, automatic roll filters, and various combinations of filters, provided by a systems supplier are designed to match standard dimensions for air handling units. It remains, however, to be decided which types of filter are best suited and most cost-effective for the performance required.

Specifically, a basic question to be answered is whether prefilters (primary, relatively coarse filters), EUROVENT Classes EU1-EU4, are suitable on their own, or need to be backed up by fine (second-stage) filters, Classes EU5-EU7, at additional cost. Prefilters normally only remove dust particles down to the order of 5 μm. Applied to centrally heated offices and similar buildings, the amount of finer dust particles remaining in the air after a prefilter can be considerable, calling for interior cleaning or redecoration at relatively short intervals, typically on a two to three year cycle in urban areas.

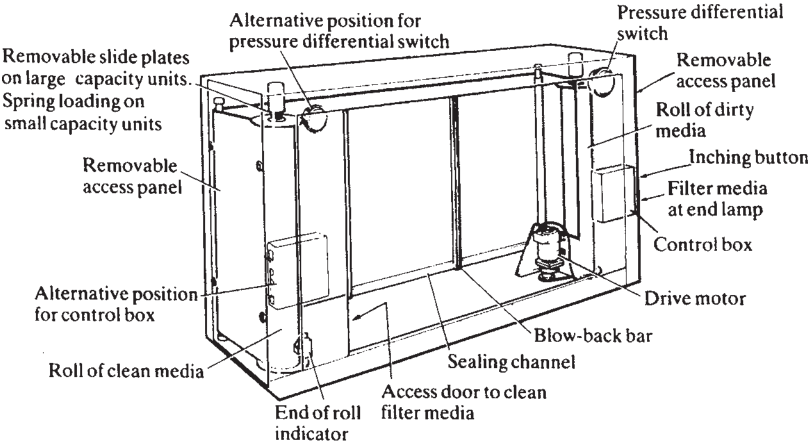
Second-stage filtration, using fine air filter media, to filter down to 1 μm could considerably extend these periods, with reduced building maintenance costs, at the expense of increased capital and operating costs for the filter system. Potential savings could be even more significant in large department stores, etc, for reducing both redecorating costs and the amount of shop-soiled goods. Unfortunately, there is no short cut to filter cost savings here, as it is impractical to provide fine filtration at a primary filter stage. Equally, to dispense with prefiltering and rely on fine filters only, or even extra fine filters (EU8 or 9) would materially reduce the performance and life of the disposable elements used with fine filters.

Prefilters

For prefilters the choice of type will normally be between panel filters, pocket filters and automatic roll filters (Figure 6.10). The first two are cheaper to install, but generally more expensive to maintain. Efficiencies are relatively low, but with automatic roll filters generally slightly better than panel or pocket types. Increasing use is being made of synthetic media in any of these types, and of automatic viscous screen filters, where efficiencies are generally much better. As a general guideline, panel and pocket filters are almost universally used for building systems handling air flows up to 4000 m^3/hr, and automatic roll filters with disposable media, or automatic viscous screen filters for larger installations.



Pleated flat panel filter Pocket panel filter



Automatic roll filter

Figure 6.10 HVAC prefilters

Fine filters

Where cost-effectiveness or initial capital cost is not a critical factor, flat panel fine filters can be combined with pocket type filters, to provide second-stage filtration, or electrostatic filters may be used for the retention of even finer particles. If the latter are of the dry type, collection of dust from the electrostatic filters must be by pocket or automatic roll filter. Dry-type electrostatic filters usually combine such dust collectors in an integral unit. Both pocket type filters and electrostatic filters are particularly suitable for variable air volume systems, where air volumes can vary from 20% to 110% of design value. Other types of filters are less effective for variable volume flow. Variable air volume systems are becoming increasingly prominent because of the energy savings that are possible.

Apart from the effect of variable air volumes on the effectiveness of certain types of filter, other system characteristics may dictate the choice of filter type, particularly as regards flow velocities. In general, the higher the efficiency of a filter, the lower the permissible design flow rate; hence in many cases it may be necessary to downgrade filter performance to accept necessary operating parameters, such as ruling out the possibility of employing a two-stage in-line filter package.

HVAC system requirements

Basically, a complete HVAC system is called upon to induct atmospheric air, clean and heat or cool it, and then circulate the treated air throughout the premises. The amount and type of contaminants present in the air will vary widely with the site of the system. In rural areas, dust concentration is likely to be of the order of 0.05 to 0.5 mg/m^3 and to comprise mainly soil erosion particles, vegetable matter, seasonal pollens and a minimum of carbonaceous matter. In metropolitan areas dust concentration is likely to be 0.1 to 1 mg/m^3, with a high proportion of carbonaceous matter, ash, silicon and other granular products. In industrial areas, the figure can be expected to be the order of 2 to 5 mg/m^3, with a large content of carbonaceous matter, as well as tarry oils and waxes, mineral and chemical dusts, sulphurous gases and acids.

Nonwoven media, made from progressively structured thermally- and resin-bonded synthetic fibres, are gaining in use over glass fibre media and are particularly suited for the filtration of atmospheric air intake and/or recirculated air in air handling systems, as well as in process intake air installations. This type of medium has a low pressure drop and a high dirt load efficiency. The material is generally available as cut sheets or pads or in roll form in lengths up to 40 m. Typical application areas include laboratories, hospitals, offices, departmental stores, schools, factories, warehouses, exhibition and conference halls, paint spray plants, clean rooms and computer centres. Additionally, a range of materials with graded density structures has been developed especially for final air filtration applications.

Disposable odour and fume filters are also used in a variety of air handling applications. The market for these filters is set to show a massive growth, with the products themselves becoming a common feature of the home and office environment. Activated charcoal filter media are used to remove many odours and fumes, such as those caused by cooking foods, cigarette smoke, some corrosive gases, decaying substances, industrial wastes and so on. Activated charcoal is particularly effective against organic odours.

Where ammonia-based odours and fumes are present, synthetic media such as nonwoven polyester impregnated with activated carbon or zeolite can be used. These filters have proved useful for removing odours in nurseries or other child care facilities, hospitals and nursing homes, animal facilities, public restrooms and so on.

Filter life tends to vary considerably with these units but, generally, if the filter is cleaned of clogging particles regularly, i.e. rinsed free of dust with plain water or vacuum cleaned, then, depending on usage, the filter could last up to six months. Air velocity, humidity and temperature all, obviously, have an influence on the effectiveness of odour-removing filters.

Stand-alone air purifiers

Air purifiers or air cleaners are gaining in popularity for use in offices and private homes. These units, which stand alone in a convenient corner of a room, can be effective for the removal of dust, pollen, tobacco smoke and odours. They generally comprise two- or three-stage filtration, using electret filters of disposable woven or felted glass fibre. Typical air flows range from 150–2200 m^3/hr. The units can also be wall or table top or ceiling mounted, and provided with variable speed selection.

Industrial air filtration

In factories, a dirty atmosphere can produce an unpleasant working environment, reduce operator efficiency, shorten the life of machines, increase maintenance costs and contaminate products. The problem of air treatment is aggravated by the abnormally high concentration of heavy and/or abrasive contaminants in the industrial atmosphere. Full control may be beyond the scope of conventional filtration systems (or be uneconomic to apply). In this case, special dust collecting treatment may need to be applied to specific areas (a topic further discussed in Section 6D).

Industrial dusts may range in particle size from 1 mm (1000 μm) down to about 1 μm or even down to 0.1 μm in the case of cupola dust, foundry dust, electric arc furnace dust and paint pigments. The current state-of-the-art surface finishing applications call for super-fine air filtration of the air supply side of paint spray plants and down-draught paint booths. The most important criterion in this technology is to prevent painted surface damaging particles 15 μm and larger from migrating downstream after collection in a filter, due to vibration in the system. Generally speaking, the usual air-conditioning industry test methods tend to group air filters by arrestance and dust spot efficiency without separating out those that do not conform to the 15 μm and larger test criteria. The particle sizes that can cause visible paint damage tend to be in the 15 to 40 μm range.

When choosing an air filter medium, it may be preferable to select one that has been tested using a test dust of non-adhesive free running aluminium oxide particles and proven to have collected this dust without unloading under vibration.

The basic central air treatment plant will have a primary filter at the plant inlet, to protect the air conditioning units, especially the heat exchanger, a humidifier and the circulating fan. There is then, finally, a second-stage filter to provide finer filtration, sited just before the outlet duct from the plant. The cost of ultra-fine filtration usually prohibits its use for a general factory scheme, it being usually restricted to point-of-use areas, especially clean rooms.

HEPA and ULPA filters

Very fine filtration can be provided by individual air inlet filters where flow volumes and flow rates are lower and higher pressure drop is tolerable. Here high efficiency particulate arresting (HEPA) filters and ultra low penetration air (ULPA) filters (EUROVENT Classes EU10 to EU17) are a particularly attractive solution, although many filter modules are designed to take alternative types of panel or cartridge media. The greater resistance to flow of the ultra-fine filter medium can be offset by increasing the filter area as the actual size of the module is rarely critical.

Table 6.3 shows the many standards for efficiency testing of HEPA and ULPA filters. New classifications have been defined for both types of filter according to EN 1822 and these are given in Table 6.4. The system is based on letters and figures in the same way as for coarse and fine filters according to the EUROVENT Classes, with H standing for HEPA and U for ULPA. The filters are then divided into eight classes from H10 to U17, depending on their efficiency at the most penetrating particle size (MPPS) and the size of the leaks.

Table 6.3 HEPA and ULPA test methods

Standard or guideline	Country	Aerosol and its detection			Efficiency	Flow resist.	Classification	Design spec.	Leak limits
		Material	Average size[2]	Detection					
BS 392B (sodium flame)	GB	NaCl salt	0.60 µm	Mass rel.	✓	✓	–	–	–
Eurovent 4/4	Europe	NaCl salt	0.60 µm	Mass rel.	✓	✓	✓	–	–
AFNOR X44013	F	NaCl salt	0.60 µm	Mass rel.	✓	✓	–	–	–
AFNOR X44011 (uranine)	F	Uran. Salt	0.15 µm	Mass rel.	✓	✓	–	–	–
DIN 24184	D	Paraffin oil	~0.45 µm	Area rel.	✓	✓	✓	–	✓
M 7605	A	NaCl salt	0.60 µm	Mass rel.	✓	✓	–	–	
SWKI 84-2	CH	NaCl salt	0.60 µm	Mass rel.	✓	✓	✓	–	[1]
Mil. Std. 282 (DOP)[3]	USA	DOP oil	0.30 µm	Area/quant. rel.	✓	✓	–	–	–
Mil. Spec. F-51068F[3]	USA	DOP oil	0.30 µm	Area/quant. rel.	✓	✓	–	✓	–
Mil. Spec. F-51477[3]	USA	DOP oil	0.30 µm	Area/quant. rel.	✓	✓	–	✓	✓
IES RP-CC00113-93[3]	USA	DOP oil	0.30 µm	Area/quant. rel.	✓	✓	–	✓	✓
IES RP-CC00711-92[3]	USA	DOP oil	~0.18 µm	Quantity rel.	✓	✓	–	–	–
prEN 1822 (Jan. 1995)	Europe	DEHS oil	MPPS	Quantity rel.	✓	✓	✓	–	✓

[1] Reference is made to DIN 24184.

[2] Mass related average diameter.

[3] All these test methods use the same test aerosol and the same aerosol detection technique.

Table 6.4 EN 1822 classification

Filter group	Filter class	Minimum MPPS* efficiencies (%)	
		Integral efficiency	*Local efficiency (leaks)*
H	10	85	–
H	11	95	–
H	12	99.5	97.5
H	13	99.95	99.75
H	14	99.995	99.975
U	15	99.9995	99.9975
U	16	99.99995	99.99975
U	17	99.999995	99.999975

*Most penetrating particle size.

An ULPA filter is thus defined as a filter having an efficiency greater than 99.999% for particles in the 0.1 to 0.2 μm size range. HEPA and ULPA filters usually consist of flat panel frames (as in Figure 6.11) containing a mass of deep pleated filter medium, so as to offer a maximized area of filter medium to the air stream flowing through the filter. The panels are covered front and back with some kind of retention screen, offering as little resistance to flow as possible. The medium of choice is a glass microfibre paper or synthetic polymer fibre (spun-bonded or meltblown). HEPA and ULPA filters made using a cold forming technique and a thermal embossing technique are a popular choice. In the case of thermal embossing, pleat depths of up to 280 mm can be achieved.

The filter elements in the form of a V-block, with mini-pleated media, are not used in these laminar flow applications, since the double deflection of the air stream as it passes through the filter, as well as the vertical supports for the pleat packages, do not permit low turbulence flow conditions.

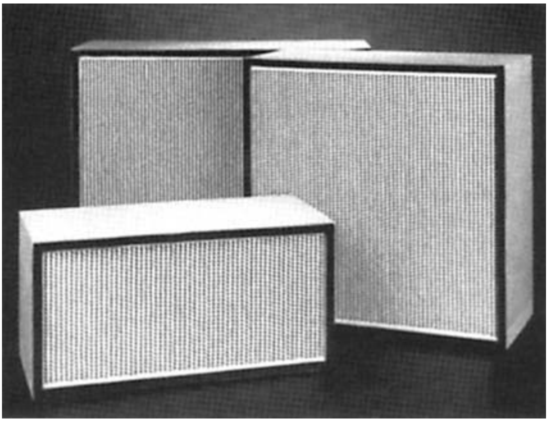


Figure 6.11 ULPA panel filters

Clean rooms

The rapid development of microelectronic semiconductor technology, with the increased storage density of current very large silicon integrated (VLSI) circuitry requires clean rooms of class M1, in which the air needs to be over 350 times cleaner than in a basic class M3.5 and the filters should have penetrations and leaks up to 1000 times lower than normal. The filter requirements are met by the higher grades of HEPA and ULPA filter element. The clean room concept has spread to several industries where an increasing need is being felt for manufacture under ultra-clean atmospheres – especially in pharmaceuticals and bioprocessing.

A basic clean-room system will normally be connected to a factory's central air treatment system, with HEPA/ULPA filtration as close to the clean room as possible (Figure 6.12). The figure shows two different clean room arrangements connected to the air-conditioning system's manifold, each with high efficiency filters as near as possible to the air outlet into the room concerned. The very clean inlet air is optimally mixed with the room air so that the desired degree of purity is achieved.

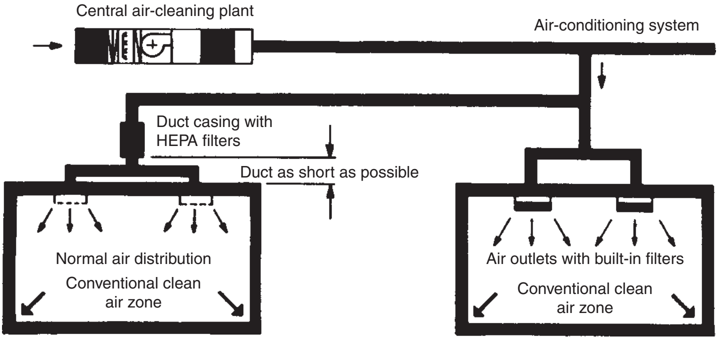


Figure 6.12 Conventional clean-room system

The high efficiency mechanical filters are fitted as near as possible to the air outlet to enable the clean air to be distributed using conventional units such as diffusers, flaps and perforated panels, as shown in the left hand room of Figure 6.12. The technical equipment is outside the clean room. This enables the filter changing to be carried out also outside the clean room. The duct in the filter region may or may not be enlarged depending on the rated flow velocity and the size of high efficiency filters used.

An alternative system is shown in the right hand room of Figure 6.12. This method of fitting filters gives several advantages: the air filtration takes place directly at the point of room entry; the filters also fulfil the function of distributing the air. This arrangement is of particular benefit for updating existing systems.

Possible arrangements for filters in laminar flow clean rooms are shown in Figure 6.13, to create low turbulence displacement (i.e. laminar) flow. Air is initially fed from a conventional central air-cleaning plant with second-stage filtering. A local air-conditioning plant is installed (right hand room in Figure 6.13) for the recirculating air, which is fed to the room through a filter wall or ceiling, providing a third stage of filtration, and laminar flow through the whole room. This requires a flow velocity between 0.25 and 0.5 m/s. A large filter area is therefore necessary to provide a high volume flow, perhaps occupying the whole area of the wall or ceiling.

Where only a small part of the overall clean room requires laminar flow, the system shown in the left hand room of Figure 6.13 may be used. Here the bulk of the room is fed from conventional air filters, with the workplace zone fed by a separate laminar flow filter.

In the food processing industry the concept of total contamination control is the main objective, and the same standards are being applied as for the pharmaceuticals sector.

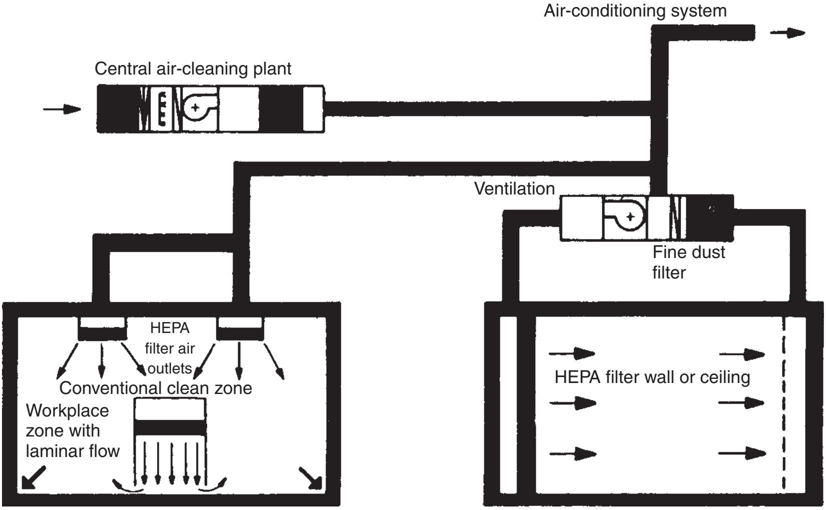


Figure 6.13 Laminar flow clean rooms

Protection using low turbulence air flow permits germ-free air to move on parallel streamlines. The recommended velocity for vertical flow is 0.3 m/s, with 0.45 m/s recommended for horizontal flow. This is equivalent to an air flow rate of 1000–1500 m^3/hr per m^2 of room area – very much higher than typical air-conditioning systems.

Generally, in the planning of a clean air protection scheme, it is important to limit the extension of the area protected with low turbulence displacement air flow to the absolute minimum, using the spot protection principle with restricted local use of displacement air flow, where it is feasible to do so.

6C. FUME AND VAPOUR EMISSIONS

Section 6B has been almost entirely concerned with the filtration of air at the entry to a workspace or living zone. Equally important are the situations where a process is generating fumes, vapours and dusts, from which people living or working in the neighbourhood must be protected. Fume and vapour emissions are covered in this chapter, mainly concerned with relatively low concentrations of contaminant, with dust collection in the next, Section 6D, where contaminant concentrations can be higher.

Legislation places the onus firmly on the employer to be responsible for worker protection against fumes and vapours at the place of work. A European Union Directive, for example, formalizes an approach for worker protection in industry, which is embodied in a range of national regulations.

Industrial fumes may consist of ‘dry smoke’, such as is given off by welding operations or certain machining operations, or ‘wet smoke’ aerosols, such as oil mist or other liquid products in mist form, or mixtures of both. Such contaminants can be removed from the immediate atmosphere by extraction, which, to be properly effective, must collect the fumes at source. The heavily contaminated extract must then be filtered to provide a non-polluting exhaust.

Collection equipment

There are at least six general methods of ventilating a working space. The first and simplest involves natural ventilation, where the room’s doors and widows are left open. The advantage of this method is that there is no additional investment, but it does not directly solve any problem of fume or vapour emission on the premises, and there is a high heat loss in winter.

The second also involves general ventilation of the room (Figure 6.14), without filtration of the exhaust. This is achieved by means of ceiling or wall mounted fans and a high volume of air is extracted (for example, a welding workshop must have between 3 and 15 air changes per hour in order for this method to be effective). It has a relatively low investment cost, but people on the premises still inhale any toxic fumes and again there is an enormous heat loss.

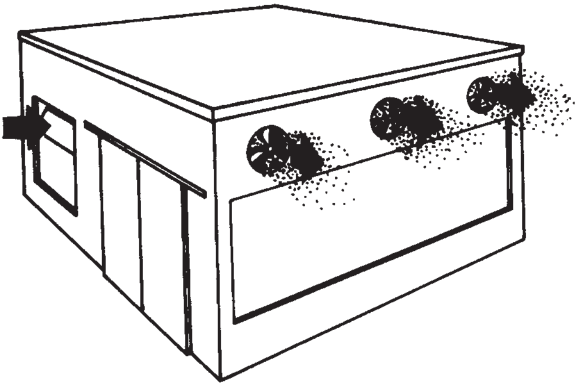


Figure 6.14 Forced ventilation

The third method involves wall mounted, flexible fume extractors (Figure 6.15), which run from the source of the fumes to an extraction manifold on the wall, so that pollutants are extracted at source and are not spread throughout the workshop. The combined exhaust is led through the exhaust fan and is discharged outside the premises, possibly through an exhaust filter. The advantage of this method is that it is very efficient, with concentrated pollutants being extracted at source. Only a small volume of air is extracted with the fumes and optional energy saving equipment is

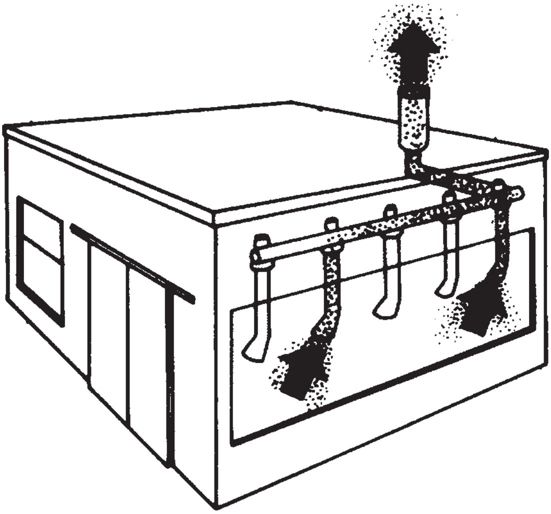


Figure 6.15 Flexible fume extractors

available. The disadvantage is that the extraction hoods must be positioned no more than 50 cm from the source of the fumes, which makes it difficult to mount such a system in very large production areas where walls or other fixed points may not be close to the operation in question.

The fourth method involves a mobile fume extractor with a built-in filter (i.e. a vacuum cleaner). This method allows the extraction at source and the extraction system can be moved to different locations. It is a very efficient process and saves energy as the air is cleaned and recirculated inside the workshop: no mounting is required and the machine is quick and easy to move. The filtration elements in the cleaner need to be either washed or replaced after a period of use.

The fifth method involves general central recirculation inside the room (Figure 6.16), through a fan-filter unit mounted on the ceiling. A high volume of air is extracted from the working areas, with 100% of the air being cleaned and recirculated. The operators do not have to position any extraction hoods, and the heat loss is much reduced. The disadvantage is that there is no specific extraction at source, and people on the premises can inhale toxic fumes before they are filtered. Special filters are required when toxic gases are present and, of course, all filters must be washed or replaced regularly.

The final method uses wall mounted flexible fume extractors (Figure 6.17) with a manifold to a central extraction unit (with the previously mentioned disadvantage of connecting the flexible extractors to a convenient manifold). The system provides extraction at source and 100% recycle of the heated and filtered air. This is a very efficient method with contaminants captured before they spread throughout the workshop, and it saves energy because the heat is contained within the workshop. The hoods must be positioned by the operator however, and this must be possible whilst remaining connected to the central extractor. Special filters again are required when noxious gases are present, and the filter elements must be washed or replaced.

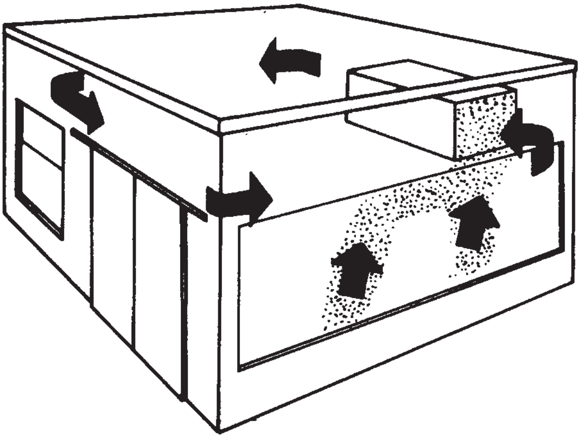


Figure 6.16 General recirculation

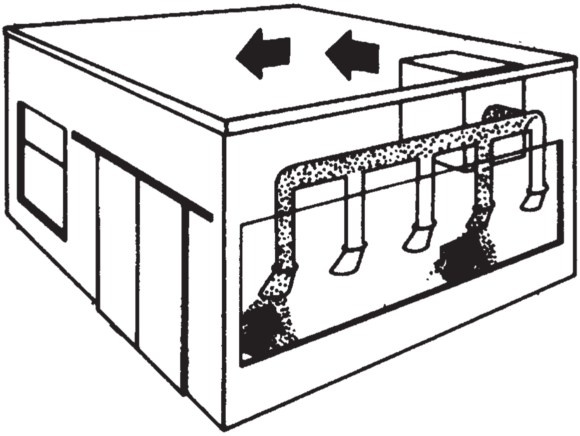


Figure 6.17 Flexible fume extraction and recirculation

As with any other effluent treatment problem, the processing of fumes and vapours should be done where they are most concentrated, before they become diluted by the surrounding air. As this is rarely possible with an individual source, especially where there are several of them in the same workshop, then this means that the exhausts should be extracted with as little additional air as possible – as in Figures 6.15 or 6.17, rather than as in Figure 6.16.

There are three basic methods of extracting unwanted fumes from the work zone.

1. Local exhaust ventilation (LEV) – hoods have been the principle tool in contamination control for many years. Hoods generally require large volumes of air, and often restrict light from the working area. The main problem with LEVs is

that the distance from the source of contamination to the hood is critical and the operator cannot be relied upon to set the system to the required distance every time, to take the fumes or vapours away. Room conditions can also affect LEV systems, particularly where unenclosed hoods are used. Cross-draughts and general room air movements can all detract from containment efficiency. Unless the material evolved is very innocuous, or the process is operator free, then LEV hoods should generally be used only as a last resort. (Table 6.5, despite its age, shown by the inch/foot dimensions, still gives some useful information on recommended air velocities.)

Table 6.5 Recommended ventilation air velocities

Process	Type of hood	Required air velocity, ft/min
Aluminium furnace	Enclosed hood, open one side	150–200 over open face
	Canopy hood	200–250 over face
Bottle washing	Enclosed booth, open one side	150–250 over face
Brass furnaces	Enclosed hood, open one side	200–250 over open face
	Canopy hood	250–300 over face
Chemical labs	Enclosed hood, door front	100 over door opening
	Enclosed hood, open front	100–150 over face
	Down draught, table type	150–200 over table area
Degreasing	Canopy hood	125–150 over face
	Slot type, tanks up to 4ft wide	2 ft wide, 1500–2000 through 2 in slot one side 3 ft wide, 1500–2000 through 4 in slot one side 4 ft wide, 1500–2000 through 6 in slot one side Over 4 ft wide, use slots on four sides
Driers	Canopy hood	125–150 over face
	Slot type at each end, cont. dryer	150–200 over 6–8 in slot
Electric welding	Enclosed booth, open front	100–150 over face
	Canopy hood	125–150 over face
Electroplating	Canopy hood	125–150 over face
	Slot type, tanks up to 4 ft wide	2 ft wide, 1500–2000 through 2 in slot one side 3 ft wide, 1500–2000 through 4 in slot one side 4 ft wide, 1500–2000 through 6 in slot one side Over 4 ft wide, use slots on four sides
Foundry shakout	Enclosed booth, open front	150–200 over face
	Down draught, grille type	300–500

(*Continued*)

Table 6.5 (Continued)

Process	Type of hood	Required air velocity, ft/min
Grain dust, wood flour, etc.	Slot type	2000 through 2–4 in slot
	Canopy hood	500–600 over face
Grinding (disc) and sanding	Down draught, grille type	250–300 over open face
	Bench type with slot one side	2000–2500 through 4 in slot
Hand forge	Canopy hood	150–250 over face
	Enclosed booth, open one side	200–300 over face
Kitchen range	Canopy hood	125–250 over face
Metal spraying	Enclosed booth, open one side	200–250 over face
Paint spraying	Enclosed booth, open one side	125–200 over face
Paper machine	Canopy type	200–300 over face
Pickling tanks	Canopy hood	250–350 over face
	Slot type, tanks up to 6 ft wide, slot one side	4 in minimum slot, 2000–5000 through slot
Quenching tanks	Canopy hood	200–300 over face
Rubber mixing rolls	Canopy hood	200–300 over face
	Slot type	2000–2400 through 2 in slot
Soldering booths	Enclosed booth, open one side	150–200 over face
Steam tanks	Canopy hood	200 over face
	Slot type for tanks up to 6 ft wide, slot one side	1500–2000 through 4 in minimum slot
Stone cutting	Enclosed booth, open face	400–500 over face
Turning tanks	Slot type, tanks up to 4ft wide, slot one side	2 ft wide, 1700–2500 through 2 in slot
		3 ft wide, 1700–2500 through 4 in slot
		4 ft wide, 1700–2500 through 6 in slot
Varnish kettles	Canopy hood	250–300 over face
	Slot type, all round slot	2 in minimum slot, 2000 through slot

2. Fish tails – these provide a relatively high velocity of extraction over a small area. Typical applications include extraction of welding fume and the removal of oil mist for certain types of unguarded machine tools. They can be mounted so that they may be moved, either on a swinging arm or by a magnetic clamp, and should in no way adversely affect the operation being undertaken (as shown in Figure 6.18). They usually have an open, slotted area equal to the cross-sectional area of the extract duct (say, 300 mm × 60 mm for a 150 mm duct). Such a fish tail, extracting between 680 and 850 m^3/hr, may solve most problems if mounted approximately 225 mm away from the source of the fume emission. Welding fumes, because of the small area over which they are generated, may have extraction rates as low as 200 m^3/hr, drawn through extraction slots no more than 75 × 25 mm. In collecting fumes directly at source, it is sometimes necessary to ensure that solid matter, such

Figure 6.18 Fish tail extractor

as swarf, or indeed liquid droplets, are not entrained, and accordingly it will be necessary to experiment with the positioning of the fish tail to produce optimum results. The object of the exercise is to create an extraction velocity of approximately 30 m/min at the source of emission. Cross-draughts, heat and other factors will also have a bearing on the positioning and extraction rate.

3. Enclosure – ideally, fumes created by operations such as machine tool working should be totally enclosed. Such enclosures help to prevent the effects of splashing and they will completely contain fumes and odours. In the case of machine tools, many machine tool manufacturers fit oil mist extraction and filtration equipment as standard. Here, again, the degree of extraction is important. The object is to design a system having an extraction rate such that relatively clean workshop air is drawn into the fume generating zone, rather than to allow the fumes to escape around the sides of the enclosure, or when the doors are opened. In order to keep the working area under the necessary negative pressure, an air flow of approximately 4.2 m^3/hr is required for every square meter of open area around the guards. The size of the enclosure may also have a bearing on the extraction rate, as very large enclosures will naturally require a higher rate of extraction to obtain the same air change rate. The figure quoted previously will, for most applications, provide a satisfactory solution; but, again, the point of extraction may require minor adjustment. The extraction point should, where possible, be away from the working area, so as to reduce the possibility of drawing off unwanted solid matter or liquid.

Laminar flow booths contain airborne dust and vapours by inducing a flow of external air inward through the working zone and into the filtration system. The key to their safe use is for the operator to work *at the side* of the source: standing downstream offers no protection from dust or vapour, and standing upstream causes a turbulent wake in front of the source, compromising operator protection. The correct inward air velocity is also imperative: too low and dust containment will fall out, but too high and turbulence in the booth may occur. Operator exposure levels will also only be as good as the background factory's level, because the booths rely on the inward flow of a large volume of factory air and in some industries this also increases the potential of product cross-contamination. Laminar flow booths are generally best suited to operations that require enclosures no more than 1.5 m wide, handling nuisance particles with a working limit of 5–15 mg/m^3.

Downflow booths have proved to be a most effective defence against airborne dust and vapours, particularly in the food industry. They operate by creating a clean laminar air flow vertically downwards from the ceiling, pushing hazardous contamination further downwards and away from the operator's breathing zone. At low levels, the exhaust air flow is taken through a number of dust filters and HEPA filters, before the air is recirculated back to the workroom.

There are other methods of extraction, which are much less commonly employed. These include lip extractors, which may often be used around the fume creating tanks, and powerful floor mounted ducts, such as may be adopted in certain foundries.

In process ventilation, the air resistance in a duct-work system is mainly determined by the velocity of the air in that system, and to a lesser degree by its tortuosity. When fumes or dust are being extracted, a relatively high velocity must be maintained to prevent the dust and fume particles from settling in the ducting system. A velocity of 10–15 m/s is considered reasonable.

Fume filtration

Dry smoke particles may be collected by impingement filtration, using pad, bag, pocket or cartridge types of filter, with paper or synthetic media, as well as in electrostatic and electrodynamic separators. Very high efficiencies may be obtained by either method. In the case of the filters, replacement of the elements becomes necessary from time to time, whereas with the electrostatic type of unit, regular cleaning is most important. There are, however, some electrostatic units that have automatic or semi-automatic wash facilities. These, although desirable, may prove an expensive option.

Wet smokes (or aerosols) are liquid droplets ranging from 10 to 0.5 µm suspended in the air. These may be filtered by bag or panel type filters, electrostatic/electrodynamic separators, or centrifugal impaction units. The bag or panel filters are very effective and have the advantage of being cheap. However, bag changing may not be an enjoyable experience, and then the collected solids need disposal. Electrostatic units are more expensive, but more effective with very light contamination, as the liquid collected drains off the collection plates under gravity. This builds up a stain on the plates and regular cleaning becomes necessary if the separation efficiency is to be preserved.

Centrifugal impaction separators

Centrifugal impaction units offer certain advantages. Separation efficiency, although not as high as clean electrostatic separators, is still very high, down to 0.5 µm without any deterioration in use. The centrifugal action imposes approximately 1000 G on the aerosol, and consequently the collectors become self-cleaning. By their very simplicity they are easy to look after and cost little when compared with electrostatic systems.

Unlike other separation systems, centrifugal impaction separators are self-cleaning and a high separation efficiency is constantly maintained. In a typical unit, a perforated steel drum is directly driven by an electric motor, while blades in the drum's interior generate suction to draw in the oil mist through suitable ducting (Figure 6.19). Oil mist is impacted by the blades at velocities in excess of 50 m/s, and particles are forced to coalesce before being thrown by centrifugal force against the inner surface of the outer casing. Cleaned air is returned to the workshop, while pressure within the casing ensures that the liquid oil is continually drained away through a discharge duct for re-use.

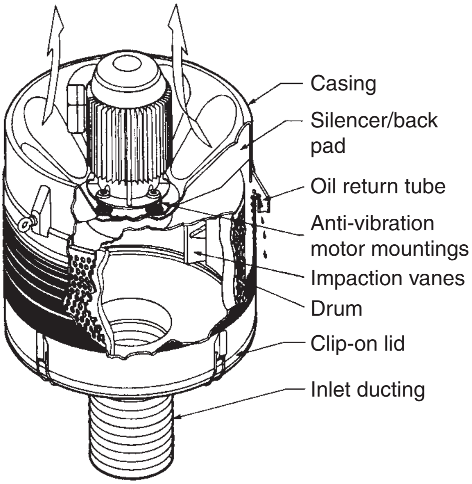


Figure 6.19 Centrifugal impaction separator

Vapour treatment

Organic solvents are widely used in industry, being used in the manufacture of many essential products, but when allowed into the environment they can become health hazards. Many solvents have adverse effects on human health, while others are photo-chemically reactive with major global effects. Collectively known as volatile organic compounds (VOCs), their emission to atmosphere is now restricted in many countries. Accordingly, solvent removal and recovery plants treat billions of cubic metres of contaminated air every day – although much effort is also being spent on discovering ways in which solvent use can be reduced (conversion from solvent-based paints to water-based, for example).

The clean-up systems are based on various technologies, the oldest of which being activated carbon adsorption. This process usually comprises the passing of solvent-laden air through specially designed adsorber vessels, containing packed beds of granular or powdered activated carbon. A minimum of two adsorbers are used if continuous processing is required. Each adsorber alternates in a cycle between an adsorption step and a regeneration step. Solvents are retained in the carbon during the adsorption step, and then they are removed from the carbon, by heating, usually with steam, during the regeneration step. The resultant steam-solvent mixture is then cooled and condensed. Water insoluble solvents can then be directly reused following mechanical decantation (and probable drying), while water soluble solvents need further separation, dehydration and possible purification, prior to re-use.

An alternative carbon adsorption technology uses the cam rotary valve method, which, unlike conventional adsorption technology that employs duplex systems, uses only a single unit that is divided into multiple compartments. On a rotary basis, a central valve in the unit distributes contaminated air to an individual compartment. While each compartment in turn undergoes regeneration, the rest are purifying the solvent-laden air. This device provides continuous, uninterrupted adsorption and uses less activated carbon.

Membrane systems are also successfully employed to recover VOCs from air streams. The membranes are used in a vapour recovery process, which combines compression-condensation and membrane vapour separation. The membrane separation step enhances the recovery possible with compression and compensation alone, allowing the process to operate at much higher recovery rates, or allowing the temperature and pressure conditions to be relaxed. This is a developing technology that shows great promise for resource recovery and pollution prevention.

Oxidizer systems

The adsorption process is intended to recover the solvent in the air stream. An alternative approach, where the economics do not favour recovery or where there are toxins present, is the destruction of the solvent contaminants. The catalytic oxidizer system shown in Figure 6.20 destroys air toxins and VOCs discharged in industrial

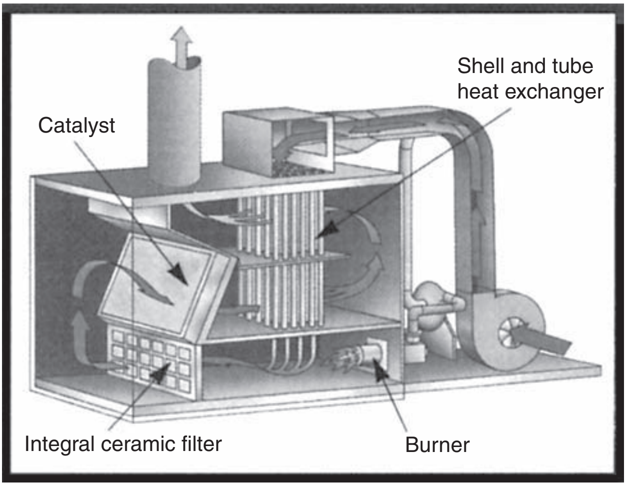


Figure 6.20 Catalytic oxidizer

process exhausts. The use of a catalyst allows the oxidation of hydrocarbons to carbon dioxide and water vapour at significantly lower temperatures than simple thermal oxidation. The process air stream enters the system fan, from which it passes through a heat exchanger, in which it is preheated. From the heat exchanger the air then passes through a high temperature-resistant filter, which protects the following catalyst. In the catalyst an exothermic reaction oxidizes the VOCs and other contaminants, raising the gas temperature, so that it can be used to heat the incoming air, before being exhausted to the atmosphere.

The catalytic oxidizer needs little or no added fuel provided that the solvent content of the air is high enough. Where insufficient VOC material is present to maintain combustion, extra fuel is added in a thermal oxidizer, such as the regenerative oxidizer shown in Figure 6.21. This has two insulated, vertical thermal energy recovery chambers, connected by an inverted U-shaped insulated oxidation chamber. Flow diverter valves are located under the energy recovery chambers to divert the process air flow into and out of chambers. The energy recovery chambers are filled with ceramic material that provides for the recovery of up to 95% of the oxidation energy. The complete operation of the oxidizer system is controlled by a programmable logic controller.

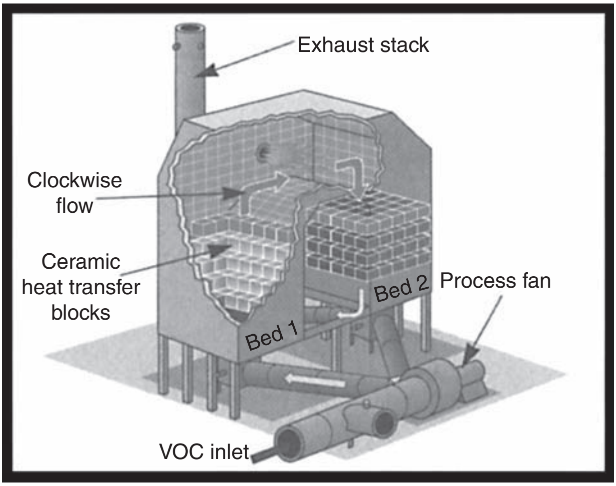


Figure 6.21 Regenerative thermal oxidizer

Biofiltration

Biofiltration is the name given to the technique used to remove undesirable components from industrial waste gases by means of micro-organisms. Waste gases are forced through layers of filter material on which micro-organisms have been immobilized. After the contaminants have been absorbed into the active surface layer, the micro-organisms break them down and transform them into products such as carbon dioxide, water and mineral salts. The filter works in a similar fashion to that of the trickle filter used for water wastes, and is based on the microbiological degradation mechanism found in nature.

In operation, waste gases are collected and fed to the filter system. Before entering the filter itself the gases may require dedusting, cooling or dehumidifying. The gas is then propelled by fan assistance into the filter, where it is distributed evenly over the filter bed, passing through layers of the filter material that have previously been inoculated with cultured micro-organisms. The strains used vary according to the components to be removed from the gas stream; for example, nocardia cultures will be used for styrene fumes, hyphomicrobium for methylene chloride, and thiobacillus for hydrogen sulphide. As the polluted gas stream passes through the filter, the bacteria consume the pollutants. Feed concentrations up to 5000 ppm are typical.

Applications include the treatment of solvents such as toluene and acetone, and of hydrocarbons ranging from simple alcohols to complex aromatics. Industries where this filtration technique is proving useful include paint, printing and plastics, and the chemical and petrochemical industries. Food processing, brewing, tanning, textile manufacture and pulp and paper are other industries that may benefit, particularly for odour removal. The advantages of the biofiltration method of waste gas treatment are low operating cost, minimal maintenance and, in contrast to wet scrubbing, the filter does not produce a polluted water stream.

6D. DUST COLLECTORS

Most of the detailed applications examined in this Handbook are concerned with contaminants that are present in their suspending fluid in only relatively low concentrations. The cleaning of gases free of dust can, however, involve quite high solid concentrations, especially where process exhausts or pneumatic conveying installations are concerned. At the highest concentrations, the usual first step is a cyclone (Section 7D), which removes suspended solids quite efficiently, and collects them into an easily recyclable state. On the other hand, there are many applications where low concentrations must be removed completely (such as fresh air treatment for machine intakes, Section 6E). The equipment discussed in Section 6C, for fume treatment, is almost all equally suitable for low levels of dust generation and treatment.

The various types of dust collector that may be used are as follows:

- fabric collectors (baghouses) – relatively inexpensive units available in a wide range of types and sizes with a capture range from 100 μm down to about 0.05 μm
- cyclones – working on aerodynamic principles with no moving parts and particularly suitable as primary collectors for dusts of moderate to coarse particle size (capture range down to 10 μm), or as precleaners for more efficient final collectors
- multi-cyclones – groups of smaller diameter cyclones, with high collection efficiency for large exhaust gas volumes containing dust in medium concentrations (capture range down to about 8 to 10 μm)
- centrifugal skimmers and other similar dry working collectors operating on aerodynamic principles

- wet collectors or scrubbers – working on aerodynamic principles in conjunction with a water spray or water wash – these include cyclone and jet type scrubbers (capture range down to 1 to 2 μm) and venturi-type scrubbers (capture range down to 0.1 μm with high efficiency types)
  - viscous impingement filters
  - electrostatic precipitators – capture range down to 0.1 μm
  - oil bath dust collectors – capture range down to 1 μm
  - oil mist collectors – specifically designed to trap and remove oil mist
  - fume extractors – hoods, fish tails and enclosures, equally capable of treating dust generation, and
  - fume collectors – such as activated charcoal or similar adsorbent filters.

Fabric filters

Fabric filter collectors (widely known as baghouses, since the collecting elements are usually filter bags) have a wide range of applications for dust removal from air or gas streams, with quite a wide range of inlet solid concentrations, and a potential performance superior to that of most other types of separators and collectors. Fabric filters generally employ the same method of separating particulate material from the air stream. Dust-laden air flows through a fabric tube or envelope, where particles larger than the interstices in the filter medium are deposited by simple sieving action. A mat or cake of dust is quickly formed on the air entry surfaces of the fabric. The dust cake then acts as a highly efficient filter, capable of removing sub-micrometre dusts and fumes, while the fabric then serves principally as a supporting structure for the cake.

In terms of an efficiency rating, nonwoven filter fabrics (felts and spunbonded fleeces) are more efficient than woven fabrics, since the open areas are smaller. Any type of fabric can be made more efficient by using smaller fibre diameters, closer weaving or packing, and a greater weight of fibre per unit area of fabric. Increasing efficiency, however, naturally means a reduction in permeability and also in cleanability.

Filtration efficiency is not a constant parameter with fabric filters. Efficiency increases, and permeability decreases, during service, because of the cake effect, and is normally higher after use and cleaning than its new, as-made efficiency. The selection of fabric is thus essentially a compromise among efficiency, cleanability and permeability.

No fabric dust collector can be made 100% efficient, but with proper fabric selection, adequate sizing and good design, a baghouse can operate at efficiencies well in excess of 99%. The performance characteristics of a fabric filter would normally follow the types of curves illustrated in Figure 6.22. The end-point of a cycle of use, when the fabric must be cleaned, is when the resistance to flow causes a reduction in air flow to a value below an acceptable minimum (although, as will be shown later, a baghouse can be operated with individual element cleaning, so that the filter can run continuously).

Some actual curves for efficiency (against fed dust particle size) and pressure drop (against time from last cleaning) are shown in Figures 6.23 and 6.24, featuring three different filter media: a needled felt, a needled felt after calendaring (surface treatment by passage between pressurized calendaring rollers) and a microporous,

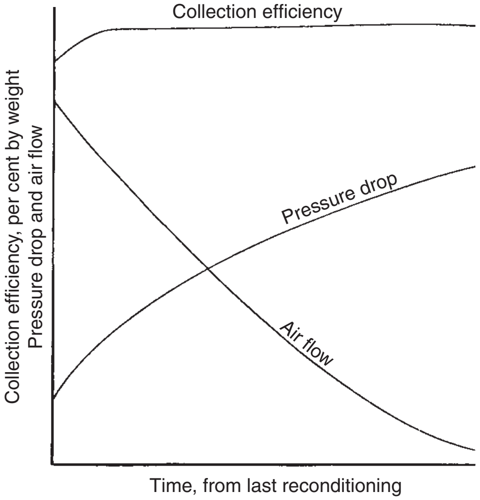
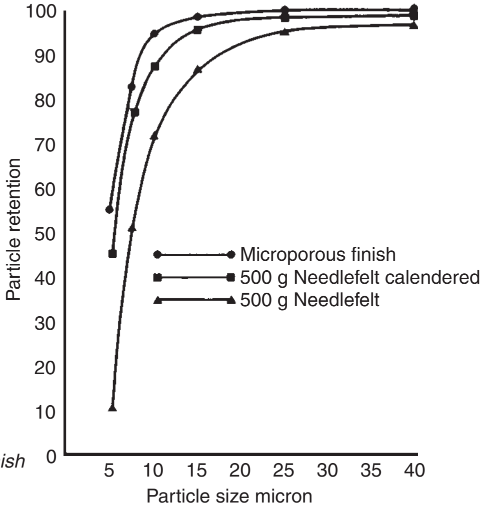


Figure 6.22 Typical filter bag performance

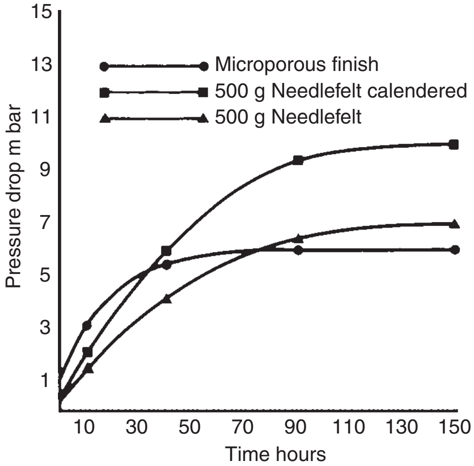


Comparison of microporous finish against needlefelts: particle retention versus particle size.

Figure 6.23 Particle retention efficiency

spun-bonded fibre material. The major difference between the needlefelts and the microporous fibre media is the greater proportion of depth filtration with the felts.

One method used to improve the efficiency of a fabric dust filter medium is to apply a coating to the upstream face of the material. This can be sprayed on, or laid down as a membrane on the substrate (often a needlefelt). The membrane would consist of a large number of fine pores, which effectively carry out the filtration, restricting the particles to the surface of the membrane and thus preventing blinding due to particle penetration into the body of the substrate. The needlefelt provides



Comparison of microporous finish against needlefelts: pressure drop versus time.

Figure 6.24 Pressure drop increase with time

the membrane with the mechanical strength to withstand the wear encountered during use. Although giving excellent results, this layered membrane is limited in use by cost to dust filtrations that suffer from severe blinding and/or dust release problems, rather than as a generally applicable dust collection medium.

Application of a membrane to a needlefelt substrate involves the bonding of the membrane to the substrate to give a laminate. An alternative approach is to apply a microporous coating to the needlefelt substrate, to act as the septum. Unlike the membrane the coating cannot exist independently of the substrate. A fine cellular structure can now be produced by applying a polymer emulsion (by specialized coating methods) to a textile substrate. In this way, it is possible to produce a coating that remains stable throughout the coating process, resisting collapse before fully drying, and forming a regular cell structure on the substrate surface. The coating is dried without curing the polymers, thus allowing further processing to provide a microporous surface membrane. Typical applications include the filtration of PVC dust and the collection of fly-ash from a coal-fired boiler on a shake clean collector. Such microporous finish fabrics have proved to be a significant advance in fabric filter technology.

Another factor that should be taken into account when selecting filter media is that of the stiffness of the material. Media are available in rigid, semi-rigid and flexible forms. Rigid media generally give the best filtration results, but are less able to cope with cohesive or sticky dusts, such as those with a high element of oil vapour. A semi-rigid medium can be a viable alternative if it is combined with the right cleaning mechanism.

Types of fabric filter

The basic form of a fabric filter is a large chamber (Figure 6.25), inside which is an array of similar filter elements, in number from a few up to several hundred. These elements hang vertically from a horizontal support plate, which also divides the housing into two parts, the dirty gas side, in which the elements hang, and the cleaned air side above the plate.

Figure 6.25 Fabric filter with vertical elements

The most common form of element in a fabric filter has a basically cylindrical piece of filter medium, either open at both ends (sleeve or tube) with each end sealed to the supporting cage, or closed at the bottom (bag) and sealed at the top to the support plate. The bag may actually be cylindrical (then also called a stocking) or it may be flat (pocket or envelope). The performance of bags and pockets is essentially similar for the same materials and air-to-cloth ratio, the main difference being in the usual method of cleaning. Pleated media cartridges are increasingly being used in fabric filters, quite often mounted horizontally in the housing (Figure 6.26).

Cartridges can offer savings on space and energy. These dust filter elements are generally made of cellulose blends (paper) or spunbonded nonwovens of polyester or polypropylene (fleece), including membranes. Pleat geometries vary with the different element diameters. Pleated cartridge dust filter elements can be cleaned by mechanical shaker units, by compressed air pulse-jet cleaning and reverse blow cleaning. The last of these provides a uniform cleaning effect over the entire surface of the filter element. Although low residues of dust will remain trapped by the pleated element, these are usually below the levels permitted by legislation.

The sizing or rating of a fabric filter is given directly by the air-to-cloth ratio, expressed in terms of m^3/min per m^2 of cloth (or other consistent units). The ratio in effect represents the average velocity of the gas stream through the filter medium and thus can also be expressed directly as filtration velocity. Typically this may range from 0.3–3.5 m/min, but average figures generally range from 0.6 to 1.2 m/min. The lower the dust concentration and/or the shorter the cleaning interval, the higher the filtration velocities that may be employed. Air-to-dust ratio is also influenced by the type of dust involved and the method of cleaning employed.

Fabric filter cleaning

Common methods used for cleaning the collected dust from the elements of a fabric filter are by mechanical shaking of the whole array of elements, or by low pressure

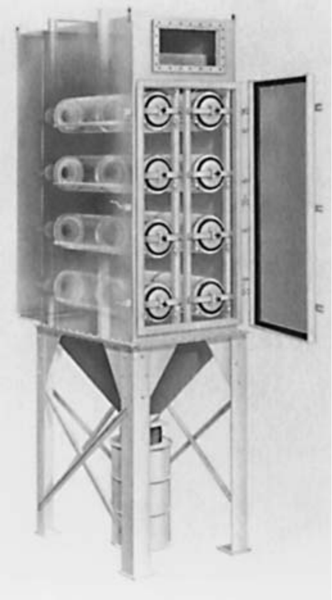


Figure 6.26 Fabric filter with cartridge elements

reverse air blowing or high pressure-reverse (pulse jet), of the whole array at one time or a section at a time, or each element in turn. The method used depends on the fabric in use, the configuration of the elements, the design duty cycle and the housing configuration. As regards the effect of the material, felted fabrics are more difficult clean and normally require pulse jet cleaning, while materials with a smooth, easy-cake-release surface can be cleaned by any method. Woven fabric elements are normally adequately cleaned by shaking or reverse flow.

Suspended bag fabric filters have a gas flow usually from outside in, so that the dust collects on the outside of each bag (which must sit on a firm wire mesh or rod cage to prevent the bag's collapsing with the pressure drop across it). A reverse flow cleaning process causes the bag to expand away from the cage, cracking the solid cake, which than falls off the element quite easily. An alternative approach, to use shaker cleaning, has the bags suspended from the sealed end, with the open end downwards (Figure 6.27). Air flow is now into each bag from the bottom, and from the inside out, with solids collecting inside the bags. The air flow causes the bags to inflate during operation and thus they do not require internal support. Used mainly for intermittent duty, the bags have their air flow stopped when cleaning is required, and the tops of the bags are shaken by a vibrating mechanism to shake off the collected dust. This operation can be carried out with air flow present, i.e. with the collector in continuous service, but in this case there is a distinct possibility that dust will be carried through to the clean air outlet; cleaning will also be less effective.

Multiple compartment collectors can be employed to provide continuous collection with automatic cleaning, simply by isolating one compartment at a time for

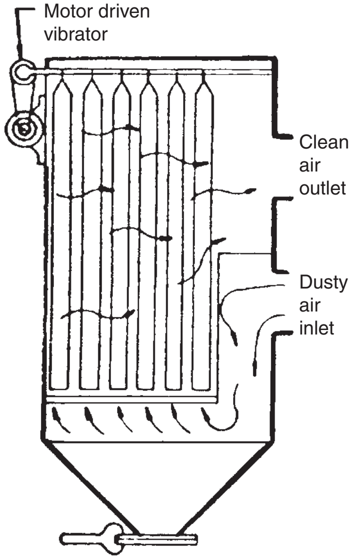


Figure 6.27 Vibration cleaning

cleaning in sequence. A further advantage of this approach, is that, since cleaning can be performed at short intervals, higher filtration velocities can be employed.

Cleaning by reverse-flow pulses of high pressure air is normally applied to fabric filters and to pleated cartridge collectors alike. The high pressure pulses may be created by a pressure blower or come directly from a compressed air supply. In the latter case the type is normally called a pulse-jet filter.

For reverse-pulse cleaning all types of filter collect dust on the outside of each element and have flow from outside to inside. Internal supports are thus necessary to prevent the bags from collapsing. The pulse of cleaning air is then introduced at the clean air side (Figure 6.28), the resulting reverse flow snapping the bags away from the supporting cage, breaking the dust cake and blowing the fabric clean. At the same time, the reverse flow deposits the removed dust in the collector or dust holder at the base of the filter, preventing any outflow during the cleaning interval (Figure 6.29).

The complete pulse cleaning cycle occurs very rapidly, within a tenth of a second or less, after which normal flow is restored. Effectively, therefore, the collector operates continuously with pulse cleaning frequency adjusted as required, typically at 1–10 minute intervals. Only a small percentage of the fabric is cleaned at any one time (typically 10%), which, together with the very short cleaning cycle, makes high filtration velocities possible. The actual filtration velocity employed may need to be limited to minimize re-entrainment of the dust from the cleaned area onto adjacent fabric surfaces. This effect is more marked with cartridge elements than with bag types.

The drawing in Figure 6.30 shows the mechanism of the pulse jet. Compressed air is fed as a short pulse from the nozzle at the top of the figure. Its passage through the

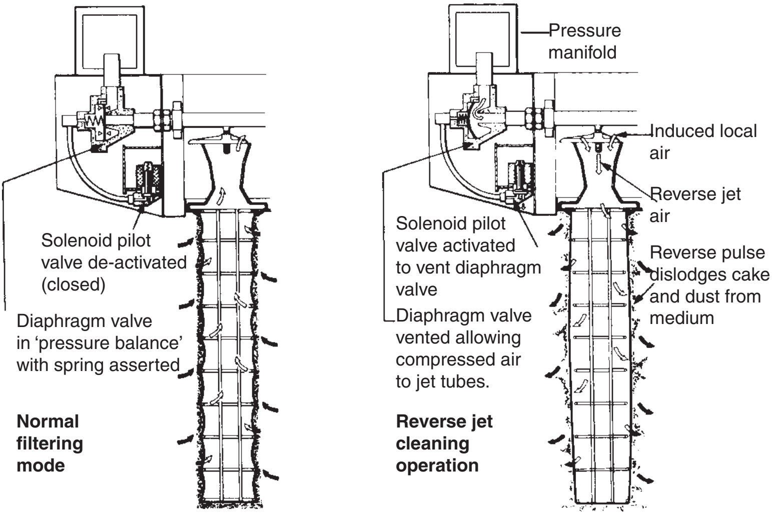


Figure 6.28 Reverse jet mechanism

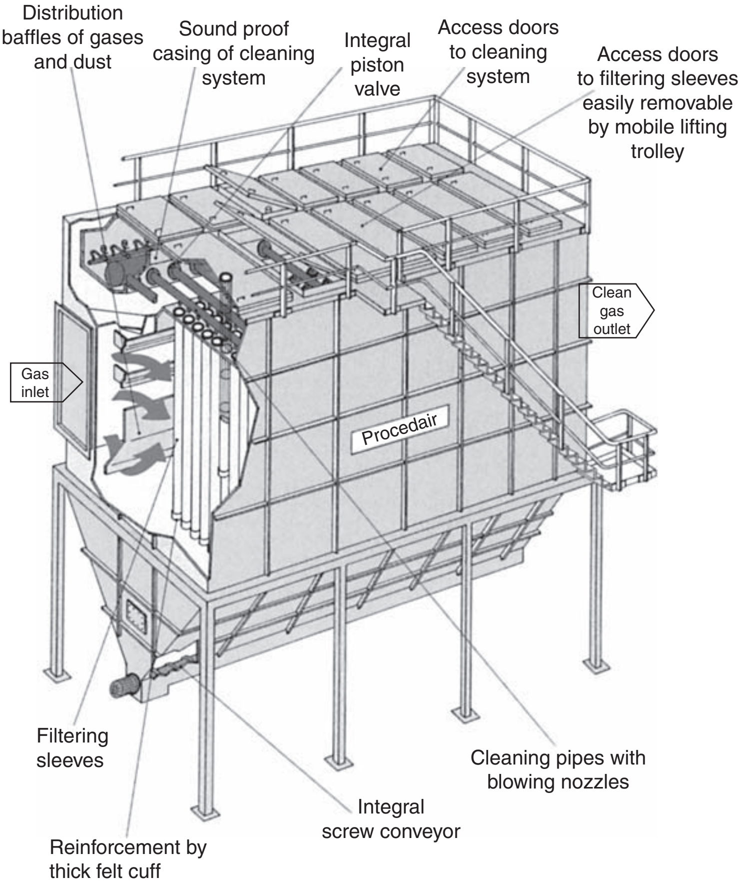


Figure 6.29 Pulse-jet fabric filter

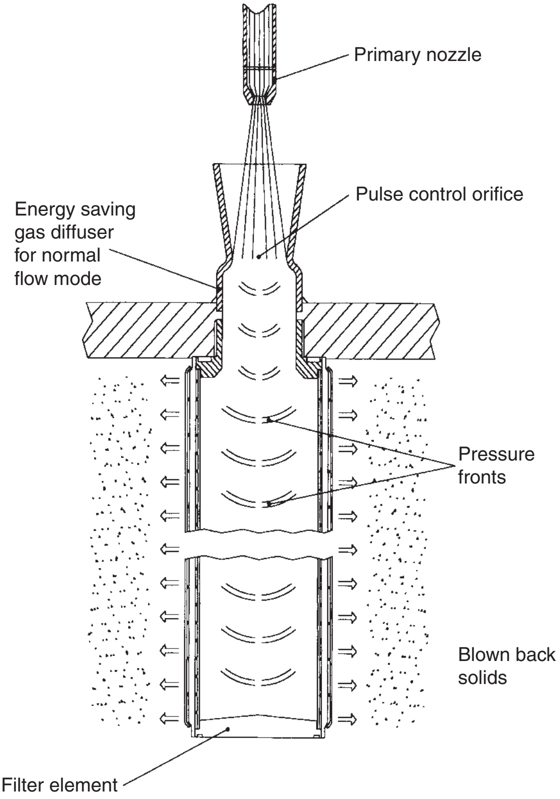


Figure 6.30 Pulse-jet mechanism

throat of the pulse control orifice generates pressure waves that travel rapidly down the filter element, blowing the collected solids off the element surface.

Legislation and social pressures are imposing tighter limits on the quality and quantity of gaseous emissions to the atmosphere. The limitations of fabric filters are imposed by the physical and chemical properties of the fabric media, which in general cannot withstand high temperatures and corrosive atmospheres. Ceramic filtration elements, with fine pore distribution, have found increasing use in a number of reverse-pulse cleaning applications, for dust removal and gas treatment, particularly where hot gases and sparks are present. Typical industrial applications include nonferrous and ferrous metal processing, coal, cement, quarries and incineration.

Exhaust (flue) gas treatment

The need to clean exhausts from industrial and power plant furnaces, and from incineration plants, and remove dusts from them, have resulted in much legislation, imposing stringent discharge limits and heavy penalties for exceeding them.

The necessary gas cleaning systems are high performance products, ranging in type from electrostatic precipitators to fabric filters (baghouses) and special filters for removal of dust and fly-ash from hot gases. Cleaning systems involve semi-dry acid gas cleaning plants, gypsum-producing flue gas desulphurization plants, and various other types of wet process gas cleaning plants, and enhanced all-dry scrubbing systems. Table 6.6 shows a range of exhaust gas applications.

Table 6.6 Exhaust gas treatment application

Steel making	Rock products	Mining
Electric arc furnaces	Cement kilns	Smelters
Open-hearth furnaces	Clinker coolers	Ore roasters
Basic oxygen furnaces	Perlite expanding furnaces	Calciners
Sintering machines	Asphalt plants	Crushing and screening
Kish collection	Lightweight aggregate kilns	Materials handling
		Pelletizing plants
Foundries	Other industries	
Cupolas	Food processing	Pharmaceuticals
Sand systems	Metalworking	Woodworking
Abrasive cleaning	Chemical processing	Coal and coke handling
Reverbatory furnaces	Grain handling and storage	
Induction furnaces		

Gas cleaning systems are designed for power stations, cogeneration plants, waste incineration plants, the cement and paper industries, the metallurgical industries and a wide range of other industries, producing polluted flue gases. Figure 6.31 shows a schematic for a flue gas desulphurization plant, illustrating its complexity.

Many different compositions of flue gases are encountered in practice. Depending on the combustion or melting process involved, the flue gases can be quite mild, or can be explosive and aggressive, while wide temperature differences ranging from 65°C to well over 450°C can be encountered.

For flue gas emission control equipment to be cost-effective, it should do the following:

- handle multiple pollutants
- have a relatively low first cost
- require as little space and present as few difficulties as possible
- be cost-effective to install, operate and maintain
- offer a potential for energy conservation, and
- be able to be applied to a broad range of industrial applications.

Air pollution control equipment in modern waste-to-energy plants accounts for around 15 to 20% of the total capital cost. Total cleaning and recycling is a process where the flue gas passes from the incineration grate to the heat recovery boiler and

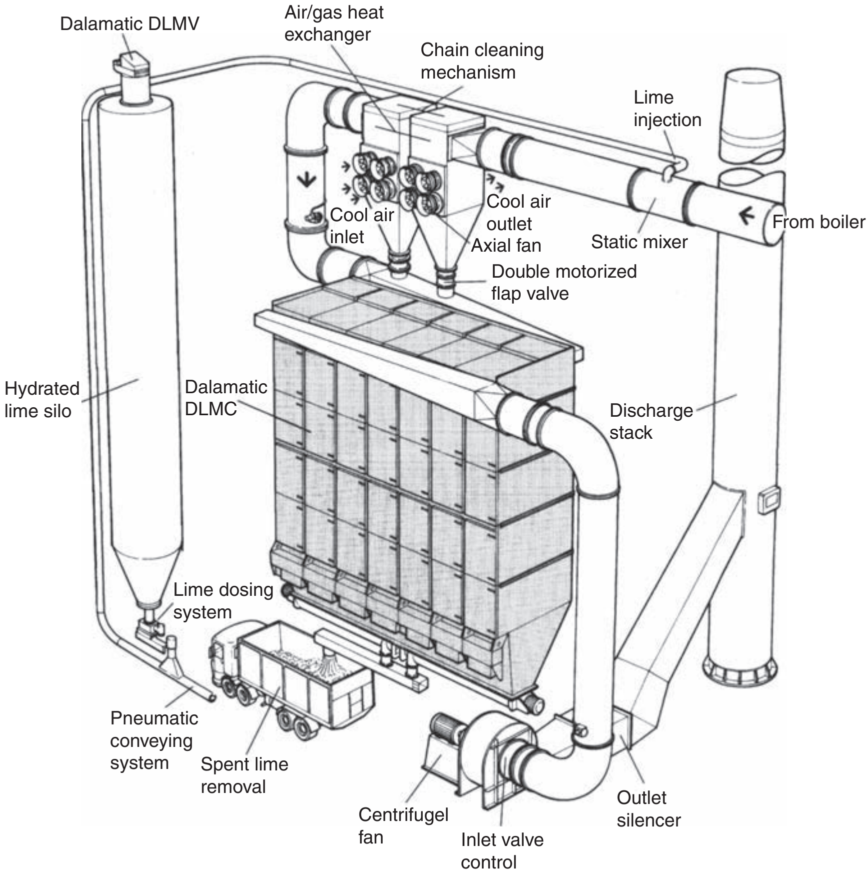


Figure 6.31 Flue gas desulphurization plant

then to a baghouse where the dust is removed. Two scrubbing stages then follow, in the first of which scrubber quenching is followed by a washout of the hydrochloric acid under acidic conditions. The second scrubber absorbs the sulphur dioxide. The scrubbing stages are followed by a second baghouse using the processes of filtration and adsorption.

Dry scrubbing

The dry scrubbing process, although developed for over 30 years, has more recently become a key unit for the treatment of acid gases, particularly in the treatment of flue gases from incineration and combustion processes. Dry scrubbers, in combination with wet scrubbers downstream of the fabric filter, to give a low water discharge scrubbing process, provide the ability to obtain extremely low emission levels of acid gases, heavy metals and dioxins.

Dry scrubbing or cleaning processes were formerly based on the passage of the flue gas through a packed bed of granular solids, either inert simply to remove suspended solids, or chemically active to remove specific gaseous components (such as acid gases). Dry processes nowadays are more likely to involve the addition of dry hydrated lime, ground limestone or a similar substance, as a powder, to the flue gas in order to neutralize the acidic flue gas components. Some reaction occurs in the gas phase, but most neutralization happens in the layer of solids caught on the upstream surfaces of the filter bags in the baghouse. Modified adsorbents (with activated carbon or coke) are also used to meet the stringent requirements regarding heavy metal and dioxin or furan removal.

Wet scrubbing

Contaminated gases can be cleaned by passage up a tower down through which a spray of liquid is falling. The liquid may be either water, or an aqueous solution chemically matched to the nature of the contaminants, or a thin slurry of the same kinds of solids used in dry scrubbing. A similar effect is achieved by passing the gas upwards through a packed bed of inert solids down over which there is a flow of the liquid absorbent.

The gas will be cooled as it flows upwards, which may be an advantage, but it will leave the top of the absorber completely saturated with water vapour, which is probably not an advantage. The result of a wet scrubbing process is to transfer a pollution problem from a gas stream to a liquid stream, which is often more difficult to treat.

Semi-dry processes

During the semi-dry gas cleaning process, a liquid, usually a lime slurry, is injected into the flue gas by means of one or more spray nozzles at the top of an absorption tower. The slurry then reacts with the pollutants. Some of the liquid will evaporate into the gas stream, and it is possible with careful flow control to arrange matters so that the effluent at the bottom of the absorber is effectively dry.

Any fabric filters used after wet or semi-dry scrubbers should not generally have galvanized support cages, because the chlorine compounds in the flue gas will react with the zinc with a detrimental effect on the filter medium. Black streaks are produced where the filter touches the support cage, thus causing a weakening of the material.

Bag filtration

Filtration systems have been a mainstay of flue and other exhaust gas cleaning for many years. The traditional baghouse (also called a fabric filter) uses an array of filter elements supported on cages and suspended from a horizontal plate inside the filter housing. This plate divides the dirty gas from the clean side of the filter, and is perforated with a regular pattern of holes to each of which a filter element is fixed. The gas flow may be from inside out (with dust collected inside the bag), or from outside in (with solids collecting on the outside surface) – the two systems having very different methods of solids removal.

The elements are most commonly in the form of a bag, closed at the lower end and sealed to the support plate at the top. A sleeve structure is also used, sealed to its support cage at both ends. Filter pockets may be used instead of bags, and so are several other element designs particular to certain applications. The filter media can be rigid or flexible, and have employed almost every type of material from which filter media are made: woven yarns (natural or synthetic), felts and needlefelts, pleated sheet, spunbonded polymers and other forms of meltspun materials, glass fibre, metallic fibre or wire, sintered powders and ceramics.

Many exhaust streams are hot, so materials must be able to work at elevated temperatures (see Table 6.7), and the gases are often chemically aggressive with sulphur dioxide and nitric acid, fluorine, chlorine and other components making the process difficult, altering the dew point conditions, and reducing the life of the filter medium. Reactions can occur between the carrier gas, the dust and the filter medium, and these are usually intensified by temperature effects. The temperature can rarely be reduced by heat exchange, since the heat exchangers rapidly foul up with dust deposits.

Table 6.7 Filter media operating temperatures

Polypropylene	90°C†	(100°C)
Polyacrylonitrile	120°C	(125°C)
Polyester	150°C	(160°C)
Aliphatic Polyamide	110°C	(120°C)
Aromatic Polyamide	180°C	(220°C)
Fibreglass		
a) felt	220°C	(250°C)
b) woven	250°C	(300°C)
PTFE	260°C	(280°C)
Mineral fibre	300°C	(350°C)
Metal fibre X CrNiMo 18/10	400°C	(450°C)
Inconel	550°C	(600°C)
Quartz	800°C	(1000°C)

† These are maximum working figures, with peak figures in brackets

Modern treated needlefelts are made from polyamides, polypropylene, PTFE and mineral fibres. Aramides (aromatic polyamides) do not burn and only lightly carburize. They are successfully used as filter media in a wide range of hot gas filtration applications. The more common applications include low shaft furnace gas scrubbing, cupola furnaces, bitumen mixing plants, waste incinerators and all types of furnaces. PTFE yarns and felts give outstanding temperature resistance, good chemical resistance, low differential pressure and high removal efficiency.

PTFE filter media are used where extremes of chemical and thermal conditions are encountered, such as waste burning, heavy fuel oil-fired systems, non-ferrous metal melting plant, slurry burners, carbon black producers, chlorine gas cleaners for PVC production and so on. Mineral and glass fibre needlefelt filter media are used where temperatures range from 180 to 300°C. They are found in dedusting of gases from electric melting furnaces and in place of precipitators in boiler firing and power stations.

Metal fibre felts are manufactured with a three dimensional textile-like surface and can withstand heavy dust load and high air flow speeds. They are used where temperatures range from 300 to 600°C for low pressure–high volume and high pressure–low volume reverse air cleaning. Ceramic filter elements made from ceramic fibres with inorganic reinforcement are used in extreme conditions for continuous operating temperatures up to 900°C. Filtration efficiency can be in the order of 99.99% with a maximum pressure drop of 100 mbar.

Fabric filters can cope with most industrial gas cleaning problems economically and efficiently. Filtering of hot gases before heat exchanging, catalytic oxidation in combination with bag filters, electrostatic precipitators in fabric filters with conductive filter media, dry scrubbing to bind the gaseous components, anti-static performance of filter materials, adhesive dust repellent finishes, and chemical protection of fibres are just some of the uses.

Ceramic filters

Conventional bag filters have severe limitations in hot gas filtration, and for hot gas-solid separation processes ceramic filters and ceramic filter candles are preferred. Ceramic filter elements, typically consisting of inorganically bound ceramic fibres, are usually self-supporting and do not need any supporting cages (Figure 6.32). The filter elements are usually temperature stable up to 900°C and, because they are almost chemically inert, they can withstand harsh chemical environments. Cleaning of the filter element is usually by similar methods to other bag or cartridge filter media, namely either by compressed air or reverse air. The pulse-jet cleaning method is probably best since the cleaning efficiency is increased. Cold cleaning gas can be used.

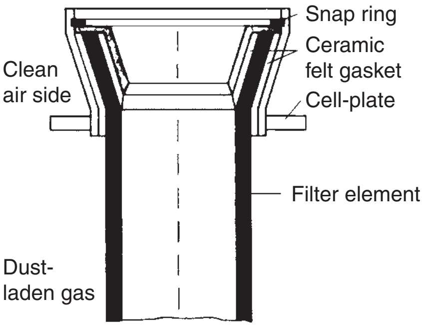


Figure 6.32 Ceramic filter element support

Ceramic filter candles have a greater tolerance to temperatures above 1000°C. They combine high burst strength and thermal shock resistance with high permeability, high filtration efficiency and corrosion resistance, in a rigid silicon carbide medium. They remove and/or recycle catalysts from any catalytic reaction system and strip catalysts from fluid catalytic cracking flue gas. They can also remove contaminants and/or recover valuable products in applications involving halogenated hydrocarbons, petrochemical processing, catalyst activations, fluid catalytic cracking, incineration of hazardous materials and combined cycle gasifiers.

6E. MACHINE AIR INTAKE FILTERS

Any machine that uses air in a combustion chamber to burn liquid or gaseous fuel must filter the air, to prevent ingress of solid particles that would cause wear in the piston-cylinder system or of the blades of a turbine. Filtration is also necessary of the air sucked into a compressor or large fan, similarly to prevent internal damage.

The simplest form of an effective machine intake filter is an element of pleated impregnated paper, housed in a suitable casing. The pleats provide both rigidity for the element, so that it requires a minimum of support, and at the same time a large surface area for filtration. This area may be further increased by corrugating as well as pleating the paper.

Some typical filters of this form of filter are shown in Figure 6.33. Air is invariably drawn from the outside to the inside of these filters, so the dust particles and other solid contaminants are trapped or stopped by the outer surface of the element, where they may cling or fall to the bottom of the casing. Filters of this type are widely used for air cleaning on internal combustion engine air intakes and similar duties, where flow rates are moderate and pressure drop must be kept to a low figure (normally not more than 0.1 to 0.3 bar).

Figure 6.33 Engine air intake filters

Variations on this simple filter include the use of pleated felts and other media, although these do not have any specific advantages over impregnated paper for light duties. Felt elements normally need support with wire mesh or similar reinforcement, to withstand pressures up to 7 bar; pleated paper is capable of withstanding pressures of that order without reinforcement. Neither type is suitable for higher pressures, even with reinforcement, without danger of disruption or at least migration of element fibres.

In the case of fabric (woven or nonwoven) filters for air intake duties, detailed design of the filter element may differ appreciably from the standard pleated form. An example is shown in Figure 6.34, where the fabric is mounted on wire gauze and folded into a star-shaped formation. This results in a high surface area, without pinching at the base of the folds, and consequently low flow velocities over the surface of the fabric. A fabric element may be preferred to a paper element for heavy duty industrial filters.

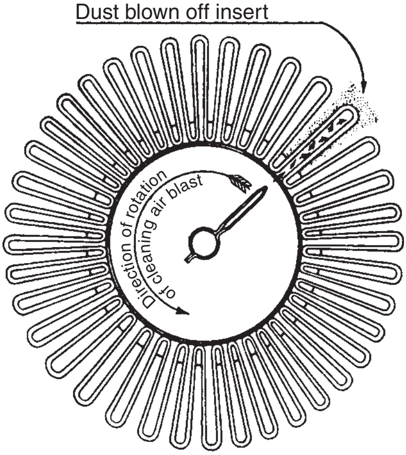


Figure 6.34 Folded fabric element

Simple dry filters may have replaceable or cleanable elements, depending on the size and design duty. Some designs provide for cleaning in place, without removal of the element, this normally being accomplished by reverse flow. A reverse-flow jet is shown in Figure 6.34, and again in Figure 6.35, where a vane is incorporated

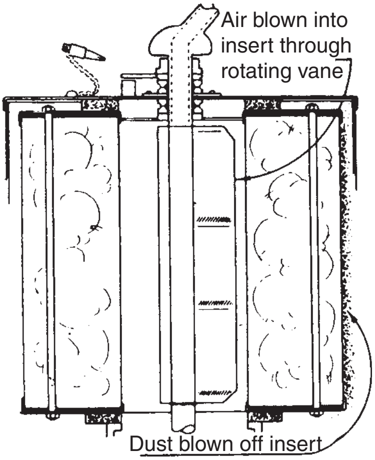


Figure 6.35 Reverse-flow cleaning

in the centre of the filter. For reverse-flow cleaning, an air supply is connected to the top of a hollow central shaft. This shaft is then turned by hand or by a motor, to rotate the vane. A blast of air is then directed into each fold of the element in turn, blowing off the dust that has collected on the outer surface.

Where flow rates are relatively high, or the air pressure is in excess of, say, 3 bar, there is some advantage in deflecting the incoming air by louvres or vanes, or by the shape of the entry into the filter housing, so that the air enters the housing with a swirling motion. The centrifugal flow pattern that results will carry solids and moisture in suspension outwards to impinge on the housing walls. The consequent loss of particle velocity will then allow the suspended material to drop to the bottom of the housing, while the remainder of the solid passes on with the air through a filter element from the outside to the inside in the normal manner. This is the principle employed in many compressed air line filters.

Single-stage air intake filters are generally used to meet a variety of air filtration requirements for engines, compressors and blowers. They are usually mounted upright, either directly on the machinery inlet or on remote air intake piping, and can be either silenced or non-silenced. They are well able to deal with pulsating flows in dirty environments, with particle removal efficiencies of 98% of all particles 10 μm and larger being typical, at capacities up to 20,000 m^3/hr.

Two-stage air intake filter/silencers are usually of the panel type and are suited for centrifugal and axial compressors.

Higher performance two- and three-stage air intake filters are typically located in aggressive environments such as steel mills, iron foundries, quarries, and power stations in desert locations. Filter panels having efficiencies in excess of 99.97% at 2–0.3 μm, following prefilters, are ideal for locations where heavy contaminant loading is a problem on air intake systems. A panel filter of this type, allowing easy element changing is shown in Figure 6.36.

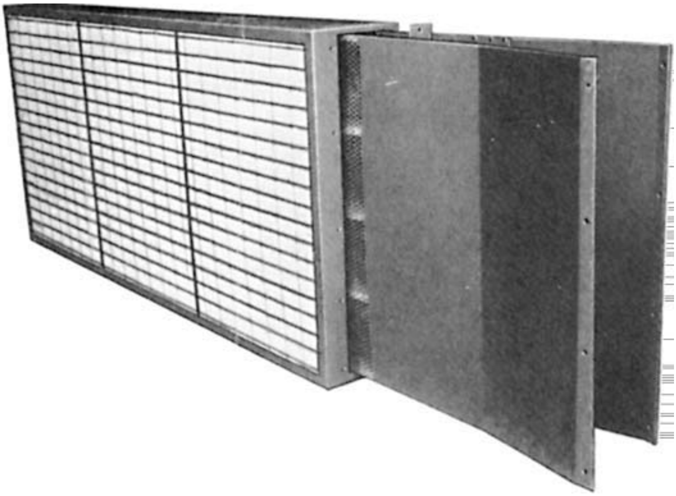


Figure 6.36 Panel filter with easily changed elements

Oil bath filters

The oil bath filter combines filtration with a viscous impingement action. In this type of filter, air is initially drawn through the oil in the bottom of the housing, with much of the suspended solid being trapped by the oil layer. The air and the remaining solid contaminants, together with an oil mist are then drawn upwards to impinge on the filter element, which is usually made of woven steel wire. This element, or screen, is continuously wetted by the oil mist and thus acts as a viscous impingement filter. At the same time, since there is a continual feed of oil mist to the filter, condensation of oil takes place on its surface and the oil falls back into the oil bath, carrying some accumulated dust with it. The filter element is thus partially self-cleaning, while contaminants continue to collect in the oil bath. Provided that the oil level is properly maintained, and that the contaminants are removed and the oil changed when necessary, the performance of the oil bath filter should be high and consistent – although the improvement in general filter media means that this type of intake filter has largely been replaced by dry filters.

Stationary installations

Stationary machines installed in factories and power stations are normally located in machine houses or separate rooms taking in air through ducting from the outside walls with suitable filters incorporated. Alternatively, the complete machine house is treated as a clean room, in which case a barrier system of conventional panel intake filters are usually installed in one wall.

For larger applications, such as gas turbines, the need for clean filtered air is essential. Typically, these systems are compact and incorporate an all-welded steel construction. The filters are usually made from uniformly pleated cellulose media, or spunbonded nonwovens, held in a steel frame, as illustrated in Figure 6.37, which shows a cutaway of an air intake system. In operation, dust-laden air enters through the weather louvres and passes through a series of filters (prefilter and fine filters). The cleaned air then moves into a clean air plenum and on into the turbine intake.

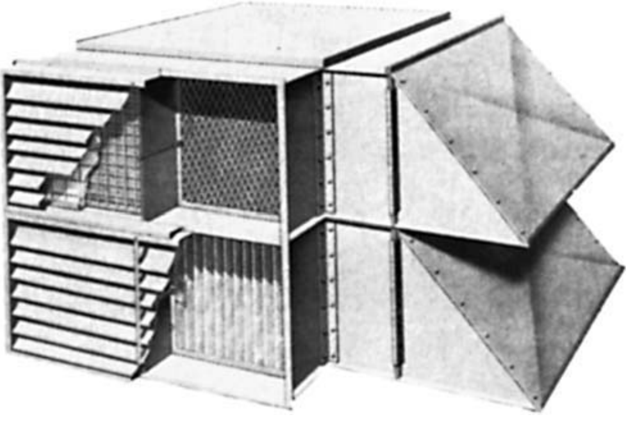


Figure 6.37 Air intake filter housing

A self-cleaning cycle can be performed by a timing mechanism, using compressed air blown in short bursts through horizontal blow pipes into the filter chamber. This brief pressurization causes the accumulated particles to become dislodged from the filter elements. The dust is then pulled by a separate air fan into a secondary cleaning circuit, which exhausts the particles to the atmosphere away from the inlet.

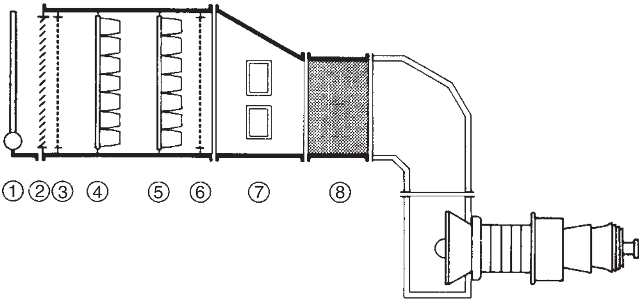
Care is necessary to ensure that the type of filter used matches both the equipment and the characteristics of the application. Specifically, a more robust filter is needed where pulsating air flow has to be accommodated.

Increasingly, the V-block filter panels, with mini-pleated nonwoven media (shown earlier in Figure 6.8), are being used for machine air intakes, especially for gas turbine systems.

Industrial air intake installations are often supplied as turnkey systems, consisting of pre-assembled modules, which are then incorporated into a basic housing. A state-of-the-art air intake filtration system would consist of eight modules:

- an anti-icing unit (depending on location)
- various protective screens
- a prefilter and final filter stages
- a transition piece, and
- a sound attenuator.

The schematic of Figure 6.38 shows all eight modules in a housing feeding a land-based gas turbine. Such systems are commonly used to filter the air supply to large engines and compressors, used for the generation and conditioning of energy.



1. Anti-icing unit (depending on the location)
2. Weather-louvres
3. Close-meshed screen as protection against small animals
4. First-stage filter wall
5. Final stage filter wall
6. Protective air intake duct screen
7. Transition piece reducing the housing size to fit the turbo machine
8. Sound attenuator and air intake duct leading to the turbo machine

Figure 6.38 Gas turbine air intake system

6F. VEHICLE CABIN FILTERS

One of the fastest growing segments of gas cleaning filtration is that of the protection of drivers and passengers in those enclosed spaces that are the cabins of moving vehicles: cars, trucks, agricultural and construction vehicles, buses and coaches, trains and airplanes. Ships are also in some need of cabin air filtration, although the atmosphere on the open sea is generally fairly clean.

The protection needs vary somewhat for these different types of vehicle: cars and trucks take in air from road level, carrying pollen, diesel soot and general atmospheric dust; construction vehicles are often working in conditions where toxic pollutants, such as silica dust, are thrown up into the working atmosphere; multi-passenger vehicles with re-circulating air systems add the need to remove infectious bacteria and viruses from their internal air systems, and this is especially so in airplanes where people are bringing home strange bacteria from distant places, where the passengers remain cooped-up for long periods, and where fresh air is more costly to acquire at high altitudes – the post-holiday cold is a well-known phenomenon.

Cabin air filtration, for cars at least, was introduced with the 1939 Nash, but did not survive the demise of that marque. Not until the mid 1980s did European manufacturers start to fit cabin air filters as standard equipment, soon followed by Ford in the USA and other American manufacturers quickly thereafter. It is almost certainly a case of application following development of suitable media – as synthetic nonwovens became available, so did it become apparent that they could be used for cabin air filtration (refer back to Figure 5.7).

The task in the private vehicle is to keep the driver awake and protected against the irritation caused by inhaled pollen, and the increasing quantity of diesel soot in the atmosphere near to the roads, especially on the well-travelled, and frequently stalled, motorways. The filter medium needs to trap particles down to sub-micrometre sizes, and, since the ‘clean’ air drawn in to the vehicle from the outside frequently smells anything but clean (again, especially on the crowded highways), adsorbent filtration may be required.

The enclosed passenger spaces of road, rail, and, especially, air transport systems require efficient ventilation and air-cleaning systems, and now it is necessary to think of microbial removal from the recirculating air, as well as the removal of dust. The filter media must now be capable of cleaning the air down to at least 0.1 μm, and probably less. The cleaning of airplane systems has become a serious problem of late, because of the increase in long-range travel.

Cabin filtration media

An important feature of the medium used to provide vehicle cabin air filtration is that it should provide large filtration areas in a relatively small volume. This means that it will almost certainly be pleated. It should also be relatively easily changed (a high proportion of private vehicle filters are never changed, partly because of the owner’s ignorance of where the filters are and/or how to change them).

The vehicle cabin filter will probably be of a shape specially designed to fit in an odd space in the cabin so as not to take up precious room needed for the driver and passengers – the filters are thus likely to be very model-specific. The typical filter for particulate solids capture will be a three-part structure – as three separate filters if there is the space available, or, more likely, as a three-layer filter medium. The first layer is the prefilter, intended to prevent coarse particles from reaching the fine filter, probably a nonwoven fibrous material, capable of trapping pollen and mould spores, and larger soot particles.

The main filter, also a synthetic nonwoven material, but now usually with electrostatically charged fibres, is capable of particle removal down to 0.05 μm. The use of electrostatically charged fibres enables the fibres to be coarser than would otherwise be the case to catch these fine particles – the finer fibres would then need a higher pressure differential across the medium. The Health and Safety Executive in the UK requires construction truck cabins, at risk from respirable crystalline silica (RCS), to have a main filter of class H11 for dust concentrations of less then 1 mg/m^3, or H12 or H13 for higher RCS concentrations.

The third layer in the cabin air filter medium is a coarser material, mainly to provide support to the fine layer.

These filter media are not expected to be cleaned when they become clogged, but to be discarded and replaced – every 12,000 to 15,000 miles for a private vehicle, or every 250 hours of operation for a construction truck.

If odour control is also required, then this may be achieved by adding a separate activated carbon filter, or by adding a layer of this material (or of nonwoven fibres in which carbon particles are embedded) to the standard three-layer particulate filtration medium.

6G. COMPRESSED AIR FILTRATION

The properties of compressed air make it a versatile and secure medium that is economic to produce and handle. Compressed air is used either as a carrier medium for the transport of energy to the point of use, where its potential and kinetic energy is converted into a driving force for pneumatic equipment, or as a process medium itself (as breathing or fermentation air, for example), or for processing purposes, such as agitating, mixing, packaging, conveying or pressurizing.

The increased purity demands of high precision, complex and fully automatic pneumatic systems, and chemical, biochemical, biomedical, electronic, pharmaceutical, and food processing operations, are the reasons for the continuously increasing needs for better quality compressed air.

A typical air sample is contaminated to the extent of 140 million dust particles per cubic metre (and more in heavily industrialized areas). As many as 80% of these particles are smaller than 2 μm – 25 times smaller than the smallest particle that the human eye can see – and most of them pass straight through compressor intake filters. These are supplemented by water vapour, along with unburned hydrocarbons from aviation, heating and vehicle fuels. When this poor quality air is compressed to 8 bar, the particle content increases to 1.1 billion particles per cubic metre. A typical analysis of the size distribution of atmospheric dust is shown in Table 6.8.

Table 6.8 Typical atmospheric dust analysis

Dust size (μm)	% Total weight
<5	12
5–10	12
10–20	14
20–40	23
40–80	30
80–200	9

The contaminants likely to be found in compressed air include:

- atmospheric dust, smoke and fumes inducted by the compressor
- airborne bacteria and viruses entering the same way
- water vapour inducted by, and passed through the compressor
- gases generated in the compressor
- oil carried over from the compressor motor, and
- solid contaminants generated within the system.

Table 6.9 shows the classes specified by ISO (in ISO 8573), for contaminant concentrations, with the lower class numbers implying better compressed air quality.

The degree of treatment required for removing contaminants from a compressed air system depends to a great extent on the intended application. For general industrial

Table 6.9 Compressed air contamination classes

Class	Solid		Water	Oil
	Maximum particle size* (μm)	Maximum Concentration** mg/m^2	Maximum pressure Dewpoint (°C)	Maximum Concentration** mg/m^3
1	0.1	0.1	−70	0.01
2	1	1	−40	0.1
3	5	5	−20	1
4	40	10	+3	5
5	–	–	+7	25
6	–	–	+10	–

Notes:

1 The quality of the air delivered by non-lubricated compressors is influenced by the quality of the intake air and the compressor design.

2 The minimum accuracy of the measuring method used is 20% of the limiting value of the class.

*Particle size is based on a filtration ratio $\beta_n = 20$. The minimum accuracy of the measuring method used is 20% of the limiting value of the class.

**At 1 bar absolute pressure, +20°C and a relative vapour pressure of 0.6. It should be noted that at pressures above atmospheric, the contaminant concentration is higher.

application, for example, such as supplying a main compressed air supply line, partial water removal by aftercooling the air delivered by the compressor, followed by filtration to remove solid contaminants down to a specific size, may be adequate. At the other extreme, two or more stages of filtration may be required, including oil removal, after which the air may be further conditioned by thorough drying to provide humidity control.

Industrial stationary compressors are normally installed in separate rooms, drawing in air from the outside atmosphere, free of factory contaminants. When the level of dust concentration in the intake air is likely to be of the order of 10–50 mg/m^3, it is standard practice to fit the compressor with an intake filter (usually a panel filter or a paper cartridge type, depending on the size of the compressor), having an efficiency of 99.9% based on the dust concentration present in the ambient air. The air intake filter can, therefore, be expected to pass all particles smaller than 5 μm, as well as a proportion of larger ones, in addition to atmospheric water vapour. It will also pass all gases, vapours, odours, bacteria and viruses.

In addition to the standard HVAC panel intake filters described in Section 6B, other types of intake filters are used (as illustrated in Figure 6.39), including:

- paper filters with renewable elements, with high filtration efficiencies (over 99%) and with a typical pressure drop for new elements of 2.5–3.5 bar if correctly sized (paper filters are not generally recommended for reciprocating compressors, unless a pulsation chamber is incorporated between the filter and the compressor intake; they are also not suitable for handling air at temperatures in excess of 80°C)

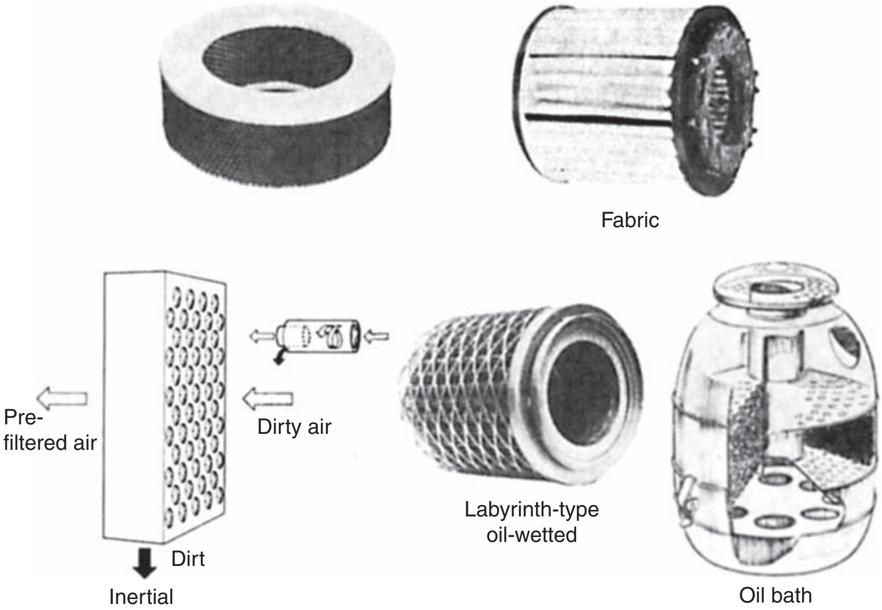


Figure 6.39 Compressor air intake filters

- fabric filters, which are stronger than paper filters and are generally cleanable by a backflow of compressed air, or in some cases by washing
- oil bath filters, which have a higher solids retention than the previously mentioned types, with a capacity for collecting impurities equal to the mass of the oil (they are not suitable for use on piston compressors, unloaded by closing the air inlet valve, unless installed with a bypass or check valve to prevent oil being blown back out of the filter with reverse air flow)
- labyrinth-type oil-wetted filters, mostly used on small compressors inducting relatively clean air – they require periodic cleaning, and
- inertial filters of the cyclone type, best used for coarse filtration of large volumes of air; they are normally used as prefilters in combination with paper, fabric or oil bath filters.

The most suitable type of intake filter is normally specified by the compressor manufacturer, based on the degree of filtration desired and the operating conditions.

Dealing with water

Ambient air always contains some water vapour. After leaving the compressor, the air is fully saturated with vapour, any in excess of saturation having been condensed to droplets. The total amount of water present is directly proportional to the temperature of the ambient air and inversely proportional to the atmospheric pressure.

This water is best removed when the temperature of the air is at its lowest and the air pressure is at its highest, i.e. immediately upon leaving the compressor. Standard practice is to follow the compressor with an aftercoolor, which should be of sufficient size and cooling capacity to reduce the temperature of the outgoing air to within 8–10°C of the temperature of the water entering the aftercooler.

Cooling in the aftercooler may be by means of ambient air or water. When cooled by water, approximately 20 litre of water will be required for every $2.5\,\mathrm{m}^3$ of free air being cooled in a typical system to realize the above performance. An air receiver installed following the aftercooler, and located in the coolest place possible will permit further cooling and water condensation. For compressors operating in the region of 8 bar, the size of the receiver in litres should be approximately equal to 30 times the rated free air delivery of the compressor in m^3/s, thus a compressor rated at $50\,\mathrm{m}^3/\mathrm{s}$ free air delivery requires a receiver of approximately 1500 litre capacity.

As further cooling may occur in the distribution mains, these should be laid out with a fall in the direction of the air flow, so that both gravity and air flow will carry water to drainlegs located at appropriate intervals in the system. These drainlegs should be fitted with automatic drain valves to prevent their becoming flooded. Any downloops in the distribution mains should be avoided if possible, but if this cannot be arranged, then a drainleg should be located at the bottom of the downloop. Except for the drainlegs, all take-off points for compressed air from the distribution mains should be taken from the top of the main, to prevent liquid water from entering the take-off lines.

Condensate

Legislation demands that oil-contaminated water be treated in compliance with the generally approved rules of engineering practice. Compressed air and gas systems produce condensate that in many cases is aggressive, as it is mixed with acidic compressor oil or includes noxious gases drawn into the compressor. For purification systems to operate efficiently, condensate has to be removed.

Condensate that is mainly water can be drained through drains with sensors and small orifices. Oil condensate must have drains with large orifices and other control methods.

The most important factor to avoid on small systems is the loss of compressed air by opening the drain valves unnecessarily. Pneumatically controlled condensate drains operate without the need for the cleaning of explosive gases or compressed air in an explosion risk area.

Time-controlled drains are generally used on systems where condensate levels are small and regular. Intelligent electronically controlled condensate drains combine pneumatics with electronic control and alarm. Large amounts of condensate can be handled continuously in this way without loss of compressed air.

Electronic condensate drains are favoured today because of their reliability over other types. Older designs of ball float traps have had a tendency to stick, resulting in either a failure to discharge the condensate, or a permanent venting off of compressed air.

New generation condensate drains have been radically improved in their design, but time-controlled solenoid valves do not always work as efficiently as electronically controlled drains that can abduct up to 1300 litres of condensate oil–water emulsion per hour.

Condensate treatment

Oil-contaminated condensate must be treated in such a way that the oil content of the water discharged from the separator does not exceed the permissible values. At present, 20 mg/l is the most widely used maximum permissible value. However, in many cases lower limits (10 or 5 mg/l) are being imposed. Whatever the limits, compressed air condensate should be regarded as a hazardous waste. An average sized compressor station with an air discharge rate of 20 m^3/min creates annually up to 60 m^3 of condensate as a waste product.

The methods for disposing of this waste involve either waste disposal or treatment. The annual average disposal cost will far outweigh the cost of a quality separation system. Oil treatment systems for compressed air condensate waste are now much more compact than a few years ago (see Figure 6.40). They consist of modular units with coalescing filters and charcoal adsorbers. Units can be connected to form a compact system. In operation, the condensate flows into a separator from the inlet, and then into an expansion chamber, where the compressed air expands to atmospheric pressure, leaving the condensate to fall to the bottom of the chamber. The compressed air expands through a demister and activated carbon bed. The condensate then flows slowly into the first of two chambers, so that no emulsion recurs and any dirt particles fall to the bottom of the chamber, which can be

Figure 6.40 Condensate treatment kit

removed for cleaning. The condensate then flows through a coalescing filter in which the oil particles become larger and float quickly to the top to form an oil film. This film of oil is then siphoned off into a canister.

The partially cleaned water then flows through a bed of activated carbon so that it is ready to pass into the effluent system. Where stable emulsions of oil and water will not separate out it is generally considered better to use an ultrafiltration membrane unit to separate the oil and water by physical means.

Centralized compressed air purification systems, incorporating condensate oil-water separators, are becoming the standard method used to avoid polluting rivers and waterways or affecting the operation of sewage treatment plants.

Dehumidification

Removal of water from the compressed air to a level where no further condensation can occur in the compressed air system (i.e. the dew point is made lower than the ambient temperature) can have definite advantages in any application, and in some can be an essential feature. Examples of the advantages of drying the compressed air include:

- supply to air tools, making it possible to lubricate them more efficiently
- the lubrication of all pneumatic components is improved when dry compressed air is used, and servicing intervals are increased

- the use of dry compressed air in spray painting equipment eliminates any risk of damage to the paint finish from water droplets in the compressed air
- in blast cleaning units, the reliability of the equipment is improved and risks of icing under outdoor conditions are eliminated, and
- in a dry compressed air system there is no corrosion, which can lead to loss of pressure and leaks.

There is also no need for draining off of the condensed water if the air is properly dried.

For most non-critical compressed air applications, a refrigeration dryer, which will give a dew point of 3°C, will suffice. Critical applications, such as those found in the food and pharmaceutical sectors, or even in car spray painting, tend to require an adsorption dryer, capable of producing a dew point of −40°C.

Water vapour is removed in what is often called a filter dryer. A desiccant dryer must be used if a low dew point is required. This uses a bed of granular adsorbent material such as activated alumina or synthetic zeolites, through which the moist air is passed. When it is fully loaded with moisture, the bed must be regenerated by various means, usually by the use of heat or pressure swing desorption. Stainless steel screens are typically used to support and retain the granules; integral polyester spunbonded pads prevent most particles generated by attrition from migrating downstream. Such dryers are usually fitted as duplex pairs, so that one can be regenerated while the other is drying the air.

Prefiltration

Downstream from the compressor, after cooler and receiver, the air is compressed and dried, but still carrying solid particles, some of which will have been generated in the compressor. A prefilter is usually installed to remove most of them. The use of a prefilter is recommended where heavy contamination by oil, water and dirt is anticipated, and is usually the first step of compressed air purification.

The prefilter using regenerable porous filter elements, such as sintered bronze powders, sintered stainless steel powders or mesh, polyethylene or polypropylene, with pore sizes of 5–25 μm, which will remove the heaviest contamination and protect the heat exchangers in the dryer. Oil- and dirt-laden compressed air flows through the filter element from the inside to outside. The coarse particles of dirt and pipe scale are retained on the inside of the prefilter. Oil, water and the remaining fine particulate matter then pass through the prefilter to a sub-micrometre filter. The use of such filters has become an essential part of achieving oil-free compressed air.

Oil removal

The problem of oil removal is complicated by the fact that oil present in compressed air can exist in three forms: liquid oil, oil-water emulsions and oil vapour. Special filters are required to remove oil vapour and oil aerosol. Modern oil removal filters are of the coalescing depth type and commonly use glass fibre elements. Oil particles of varying sizes impinge on and adhere to the fibres, resulting in a gradual build-up of coalesced drops. These drops are driven to the outside of the filter by the air stream. When the oil comes to the outside of the medium, it is stopped in a porous sock covering the element. The oil then flows by the force of gravity down to the bottom of the sock, where it drops to the filter bowl. The oil is then automatically drained from the filter. These filters are capable of removing the oil content in a compressed air flow down to a level of 0.1 mg/m^3 or less. Table 6.10 gives an internationally accepted grading system for coalescing filter media.

Table 6.10 Coalescing filter media grades

Grade	Colour Code	Coalescing Efficiency[1]	Max. Oil Carry Over[2]	Pressure Diff.[3]	
				Dry	Wet
2	Green	99.999+%	0.001 mg/m^3	0.1bar	0.34bar
4	Yellow	99.995%	0.004 mg/m^3	0.085bar	0.24bar
6	White	99.97%	0.01 mg/m^3	0.068bar	0.17bar
8	Blue	98.5%	0.25 mg/m^3	0.034bar	0.09bar
10	Orange	95%	1.0 mg/m^3	0.034bar	0.05bar
PU	None	98.5%[4]	N/A	0.017bar	n/a
AU	None	0.003ppm[5]	N/A	0.068bar	n/a

[1] Coalescing efficiency using 0.3–0.6 micron particles, based on 50 ppm maximum inlet concentration

[2] When tested per BCAS test procedure 860900, 50 mg/m^3 inlet concentration

[3] Pressure differential at rated flow. Total element pressure drop is obtained by adding together the dry and wet pressure drops.

[4] 3 micron absolute

[5] Vapour Removal 0.003 ppm

Glass microfibres are considered to be ideal filter media for the coalescing of liquid aerosols. Inherently, this material is neither adsorptive nor absorptive to liquids, and consequently is superior to natural fibre media insofar as retention of its original properties is concerned. Glass microfibres are quite hydrophobic (i.e. water repellent), so that water forms on such fibres as droplets rather than as a film, a condition that is favourable to continuing filtration efficiency. Unfortunately, neither glass nor any other material is oleophobic (oil repellent), and so oil will form as a film on glass microfibres, increasing their effective diameter. Allowance for this diameter increase, which is relatively minimal, can be made and this film of oil will not appreciably detract from filtration efficiency once the filter medium has been wetted.

Glass microfibres in the 0.5–0.75 µm diameter range usually yield the best results as a coalescing filter medium. The depth of the fibre bed and the void space to fibre space ratio, are of paramount importance to the proper operation of a coalescing filter.

Filter selection is controlled by airhandling capacity and filtration efficiency. Although the one dictates filter size and the other the grade of element, they are interrelated and cannot be considered independently. For standard systems, operating at about 7.5 bar, filter selection should begin by determining the maximum air flow at the point of filtration, i.e. the consumption of free air in standard litres per second before compression. Then the required air quality should be determined and then the appropriate grade of filter. This should be a balance between performance and the adverse economics of shorter element life that is inherent in more efficient filters.

Filter manufacturers provide easy-to-follow selection tables and charts to enable the determination of the correct efficiency. By referring to these charts a proper filter selection can be made, but it should always be borne in mind that the life of coalescing elements can be extended by the inclusion of a prefilter.

Coalescing filters require an air velocity within specified limits if they are to operate efficiently. If the total volume of system air does not require filtration to the same level of cleanliness, it will be more economical overall (i.e. capital plus running costs) to install individual filters either at the point of use, or in branch lines downstream of a T point. Air flows through these local filters will be lower than through a central filter system, allowing the use of smaller housings and extending the service life of the elements.

As far as maintenance of coalescing elements is concerned, the test is the pressure drop across the filter, from inlet to outlet. Most outlet filters have pressure indicators of one form or another. Typically when a pressure differential of 0.5–0.7 bar is indicated, the element must be changed. Figure 6.41 shows a suitably instrumented filter.

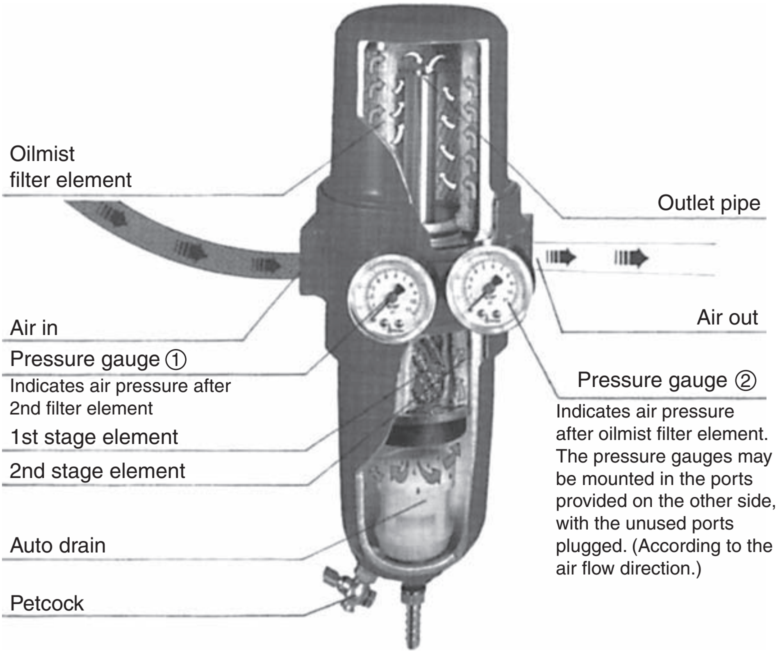


Figure 6.41 Coalescing oil filter

Although the application of coalescing filtration techniques to the problem of removing sub-micrometric oil aerosols from compressed air is relatively recent, the development work upon which they are based is not. Stairmand and his colleagues in the early 1950s laid the academic groundwork for the filtration of aerosols by means of fibrous filters. Coalescing filters for the removal of oil aerosols are rapidly moving toward overcoming a longstanding obstacle in the path of the universal application of compressed air as a process and control medium. Their usage is now widespread and the only deterrent to their total acceptance is the residual reluctance of industry to try yet another device claiming the provision of completely oil-free air.

A three dimensional layered, binder-free borosilicate microfibre web has been developed to trap 99.99999% of all oil and water aerosols and dirt particles in compressed air down to a size of 0.01 μm. These elements are chemically, biochemically and biologically neutral, and present significant advantages.

The mechanical sandwich construction of the two-stage filter element (Figure 6.42) held between stainless steel support sleeves assures high filtration efficiency, even under changing pressure conditions and flow directions. Owing to the coalescing effect of the filter medium, the elements are self-regenerative as far as the removal of liquids (oil and water) is concerned. It is advisable to ensure that prefilters fitted in the line ahead of these ultra-high efficiency filters are capable of removing particles down to 5 μm or less, as otherwise the coalescing filter may quickly become choked with dirt. As a matter of principle, such high efficiency oil filters should always be installed downstream of a dryer, where one is used.

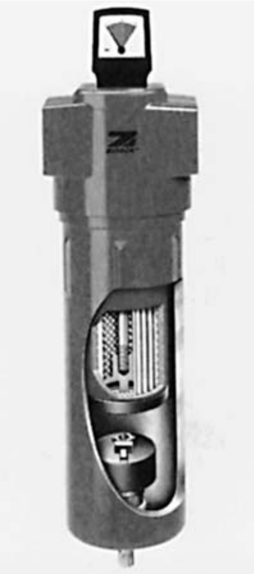


Figure 6.42 High efficiency oil filter

Other types of coalescing filters include combination units that use three basic operations of liquid-gas surface and depth coalescing, vapour phase adsorption and final particle filtration to remove free entrained water, water-oil emulsions, free oil, oil vapours, dirt particles and some types of entrained organic liquids and vapours.

Residual oil content

A test method has been established to determine the liquid oil content in air and gases under compressed conditions, as well as under atmospheric operating conditions, at temperatures from 0–100°C. This test method has a degree of accuracy of approximately $\pm 10\%$ within a detection range that is extraordinarily widely extended. The minimum oil content in the extraction solvent should be 1 ppm, depending on the sampling time.

The total system for the test comprises three components:

- sampling probe and filter holder
- the device for the measurement of temperature, pressure and flow volume as definition systems, and
- infra-red double beam spectrometer, extraction device and Freon 113 as analysing devices.

A defined quantity of air under compressed conditions is sampled from the compressed air stream. Under isokinetic conditions, the air stream is admitted through a special sampling probe to the filter holder. The oil, carried along in the form of droplets or an aerosol, is caught down to 0.01 μm in the sampling system. A special test filter is in place in the filter holder. The filter material consists of micro-fine glass fibres, in which, according to the DOP method, the permeability is less than 0.0001%, and according to the particle counting method, it has a zero penetration of particles down to 0.1 μm. The sampling time has to be fixed according to the quantities of residual oil to be expected.

The following analysis is then undertaken using the infra-red spectrometer. The oil has to be extracted from the test filter and the sampling probe, by solvent washing (using Freon 113), with the washing continued until all of the oil particles have been dissolved. From the extract an infra-red spectrogram is produced.

The infra-red absorption is measured at wave numbers 3050–2800 cm^{-1}, which is the absorption range characteristic for hydrocarbon groups. The heights of the extinctions shown in the spectrogram are proportional to the hydrocarbon concentrations in the solvent. For a known volume of solvent used, this gives the absolute amounts of the hydrocarbons extracted.

Sampling

The most difficult phase during the process of determining the residual oil content in compressed air is the sampling from the flowing gases. Figure 6.43 shows the sampling points in the compressed air system. A representative sample of contaminants being transported in the gas is only possible if the sample is taken with a specially shaped probe and only with isokinetic suction. If the sample is taken incorrectly, the results can be between 100% and 1000% wrong, particularly if the air is heavily contaminated with particles and the oil droplets are greater than 1 μm in size.

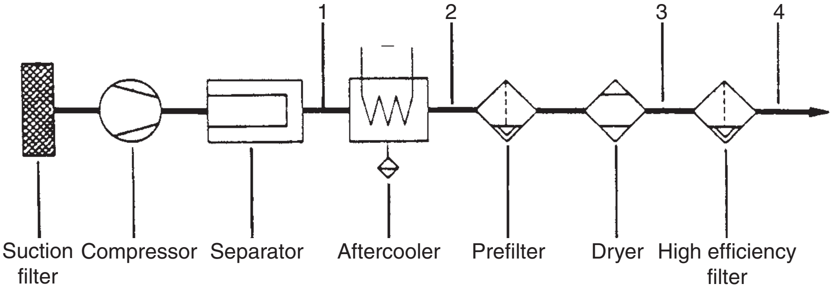


Figure 6.43 Compressed air system sampling points

Test filter

It is recommended that the special filter be of binder-free glass fibre web of the highest purity. The filtration effect down to 0.01 μm has to be better than an efficiency of 99.9999%. The filter element should only consist of solvent-resisting materials, and should not contain any extractable components. The filter housing should have a void volume that is as small as possible and it should be totally free of clearance volume.

Oil vapour

Oil-free compressed air still contains hydrocarbon vapours and odours, which in the food (especially dairy), brewery and pharmaceutical industries must be removed. To effect this removal, an activated carbon filter element should be used. Such elements are normally incorporated into another filter stage, immediately downstream of the high efficiency oil removal filters, where they should adsorb the hydrocarbon vapours and organic odours.

Filters based on activated carbon have been employed for decades to deodorize compressed air, and are particularly effective for the removal of its major gaseous contaminant, oil vapour. Compressed air may also contain many species of trace gaseous contaminants, such as the oxides of carbon and nitrogen, methane, ethylene, ammonia, sulphur compounds, and so on. Activated carbon adsorption will not effectively remove these contaminants, so that, if their absence is necessary, then chemical, catalytic or selective adsorption means must be utilized to eliminate them.

Adsorption by definition is the process whereby specific molecules (the adsorbate) adhere to the surface of a porous solid (the adsorbent). It is generally agreed that the phenomenon of adsorption occurs in stages. First a single layer of adsorbate molecules attaches itself to the surface of the adsorbent; then multiple layers form and fill the finer pores in the surface; and finally the coarser pores become filled by capillary condensation. The nature of the solid surface is thus of critical importance, and it is the process of activation that gives the required high specific surface.

Activated carbon is an excellent adsorbent for oil vapour, and is therefore highly suitable for the purification of compressed air. The activated carbon must be in a finely granulated state to provide the required large surface area, and the adsorber is usually in the form of a packed bed of granules, mounted in duplex form, so that one adsorber can be regenerated while the other is adsorbing.

Activated carbon has a selective preference for oil vapour (which has non-polar molecules) over water vapour (which is polar). Polar molecules are held in place by the attraction of ions of opposite electrical charge, whereas non-polar molecules are held using electron sharing. The strong affinity of carbon for oil vapour is of vital importance, since even 'instrument quality' compressed air contains far more water vapour than oil vapour. System conditions are also of considerable importance, since adsorption is a reversible process: temperature increase, pressure decrease and adsorbate concentration decrease all tend to promote desorption. Although system fluctuations are not usually of a magnitude sufficient for desorption to occur, they can inhibit adsorption and lower its efficiency markedly. Consequently, it is important that adsorption type filters are located where such changes in the system conditions are minimal. The adsorption efficiency of activated carbon filters should be such that the delivered air is completely free of hydrocarbon gases and organic odours.

Air line filters

Standard air line filters for distribution lines generally remove particles down to about 40 to 50 µm in size, or lower in some cases. Finer filters can be used for better protection where required, but it is more usual to use these for second-stage filtering at the take-off point to individual supplies. In this respect, line filters fall into four categories:

1. rough filters for distribution mains, capable of removing particles down to 50 µm
2. medium efficiency filters, capable of removing particles in the range 5–40 µm
3. fine filters, capable of removing particles in the size range 1–5 µm, and
4. ultra-fine filters, capable of removing particles down to 0.1 µm or better.

Fine and ultra-fine filters are normally only used for second- and third-stage filtering respectively, i.e. they should be preceded by a coarser filter to remove coarser contaminants, and to protect the finer filters from gross dirt contamination.

A properly designed air line filter of the correct size for the rate of flow will effectively remove liquid water, but cannot reduce the water vapour content of the air. If the air is subject to further cooling after it has passed through the filter, more water may condense out of the air. If complete freedom from water contamination is wanted, the air must be properly dehumidified.

Operation of an air line filter is simple. Typically, air entering the filter passes through louvres, which direct the air into a swirling pattern. Centrifugal force throws the liquid droplets and any particulate matter outward to the inside of the filter bowl. There they run downward to the bottom of the bowl and drained away. A baffle prevents the turbulent air from picking up the liquid and returning it to the system. As the pressurized air leaves the bowl, it passes through a filter element that removes additional solid impurities, before the air re-enters the air line.

Air line filters can be equipped with an automatic drain to save time and labour in the draining of collected water, especially when the filter is mounted in a hard-to-reach location. All filters should be mounted vertically, and when equipped with automatic drains, a 3 mm internal diameter drain line should be used to plumb the drain away from the immediate area.

In the selection of the best filter for a specific application, a number of factors must be weighed against each other in terms of performance and cost. The initial cost of the filter may be low, but if the element needs to be replaced frequently, replacement costs may soon outweigh the initial savings. A filter with a high efficiency rating may also have a high pressure drop, so increasing operating costs. An excessive pressure drop can also result from improper sizing or excessive flow through the chosen filter. A filter should never be selected on the basis of pipe size: compressed air filters should be sized on the basis of air flow and system pressure.

In order to prevent failures in air operated devices, means of monitoring the filter for element replacement are necessary. Most filters rely on pressure drop through the filter as an indication of elements saturation or blockage. While some require the installation of differential pressure gauges external to the filter, others are available with differential pressure gauges or indicators mounted directly on the filter housing. Some other types require a visual check on the element, either by disassembly of the filter housing and removal of the element for inspection, or by observing a built-in colour change.

Element life

Probably the most frequently asked question about compressed air filters concerns the length of the working life of the elements, before they have to be replaced. With coalescing filters element life is determined by pressure drop, and with adsorption filters by saturation.

Generally, a longer element life can be expected if the air is compressed by a reciprocating compressor. Sliding vane and rotary screw compressors have a high oil carryover so that a shorter element life can be expected. In a rotary screw compressor, the bulk of the aerosol droplets measure between 0.1 and 0.5 μm. It is therefore advisable to fit a sub-micrometre filter if oil is to be separated from the compressed air effectively. The internal oil separator is intended to minimize oil carryover into the air stream. In the event of separator failure, large quantities of oil will be released, causing, in some cases, immediate failure of the filter element.

In terms of normal compressed air demands, filtration technology know-how has developed to the point where it is now possible to improve on the compressed air quality from an ‘oil-free’ compressor fitted with a refrigeration dryer, by using an oil-lubricated compressor in conjunction with an oil-free six-stage air treatment system.

6H. PNEUMATIC SYSTEMS

Fluid power systems, as their name implies, use a fluid to transfer power from a point of generation to a point of application. Where the fluid is a liquid, usually water, the systems are termed hydraulics, and these were described in Section 5E. Where the fluid is a gas, usually air, then the systems are termed pneumatics. Unlike electricity, which also transfers power over a distance but where the transfer distance can be very large, fluid power is normally used over short distances: within a road vehicle, say, or at the most within the confines of a factory building.

Air is compressed for three main reasons:

- to act as a source of power
- to provide a source of breathing air, and
- as a process input as a reactant or an agitator.

The first of these is the technology of pneumatics, whose purpose is the use of compressed air to achieve mechanical motion in at least two important ways: to drive a tool (from a dentist's drill to a road breaking hammer) or to activate an instrument, either an indicator or a controller.

Pneumatic systems, using a compressible fluid, air, exhaust the air when the job is done, so they do not have a return line. Air, even when compressed, is light, so therefore are the transmission hoses, a characteristic also helped by the fact that pneumatic system pressures are relatively low, at 5–8 bar.

By contrast, hydraulic systems work at much higher pressures, say 60–300 bar, with a heavier, incompressible fluid (water), and therefore much heavier transmission lines. They use a closed fluid loop, with a return line and a storage reservoir.

The characteristic that both fluid power systems share is that their operating fluid must be clean, free especially of solid particles that could cause abrasion and jamming problems in the machinery that is being driven by the fluid power.

The cleaning of compressed air flows has been described in the previous chapter, but an important element of pneumatic systems is the inclusion of an air line filter ahead of any particular pneumatic tool or control system (as shown in Figure 6.50 in Section 6J).

A checklist for installing and operating compressed air line filters would include the following items.

1. Determine the type of compressor lubricant used before selecting a filter. Some filter components such as gaskets, seals and transparent bowls are not compatible with certain synthetic compressor lubricants. Deterioration of these parts as a result of contact with such lubricants may cause the filters to burst and even end in personal injury.
2. Ensure that the manufacturer's pressure rating and flow capacity of the filter are equal to or exceed the pressure and flow at the point of use.
3. Inspect the whole filter for shipping damage: in some cases, if one or more parts are damaged, then the entire assembly must be replaced.
4. Filters should be installed downstream of aftercoolers and receivers.
5. On major or critical air lines, where the air supply must not be interrupted, it is good practice to incorporate a bypass system complete with a standby filter at the filter location. This system will permit a continuous supply of air while maintenance or other work is being performed on the primary filter.
6. If the filter does not incorporate an automatic drain facility, then a drain trap or drop leg should be installed below the filter, which should be drained frequently. This will prevent liquid from accumulating in the bottom of the filter housing or impairing the efficiency of the filter element. The flow capacity of the drain system should not be exceeded on startup, since compressed air lines may accumulate large amounts of water and oil while shut down.

7. A compressed air filter is a pressure vessel. While in service, filters must be depressurized before any maintenance is attempted. The filter should be depressurized by slowly opening the drain or trap provided for condensate removal. Failure to depressurize slowly can result in damage to equipment and injury to personnel.
8. The manufacturer's warnings should be observed at all times with regard to cleaning the filter, to avoid danger to filter parts. Since some cleaning solvents attack seals, or transparent bowls or housings, these should be cleaned only with soap and water.

6I. STERILE AIR AND GAS FILTERS

The demand for sterile compressed air and gases increases all the time and selecting a sterilization filter for a compressed air or gas system can be a difficult task. The production of proteins, vaccines, antibodies, hormones, vitamins, enzymes and other biotechnology products involves highly technical processes, which require aseptic and sterile supplies of gases or liquids throughout the manufacturing cycle. The production and packaging of many food and beverage products, such as beer, yoghurt, creams and cheeses all use compressed air or carbon dioxide. Unfortunately, the nature of all these products makes them very susceptible to contamination by micro-organisms carried by the compressed air or gas.

Any product that can be contaminated by airborne bacteria must be protected against them. In the case of foods, beverages and chemicals produced by fermentation, ingress of bacteria would cause serious defects in the products, if not their complete rejection.

In the pharmaceutical and fermentation industries, compressed air and gases are in use throughout every stage of the production process from the refining of the raw material to the manufacturing and packaging of the final product. Compressed air may be used as a source of energy in a process or as a process input. Air motors are used for explosion-free mixing of powders, for air instrumentation and in cylinders for batching materials. There are many different uses for air in the energy mode, but in every case it must be free from solid particles, carry no water or oil and have no odour taint. Figure 6.44 shows alternative schemes for the delivery of sterile air.

Air for process input will include aeration of liquids, seed fermentation and laboratory applications. Air for mixing into the preparatory chemicals or the ultimate product requires to be as clean and sterile as the material with which it mixes, so there can be no question of fouling by solids, liquids or micro-organisms.

Micro-organisms, as their name implies, are extremely small, including bacteria, viruses and bacteriophages. Typically, bacteria can be from 0.2 to 4 μm, while viruses are less than 0.3 μm down to as small as 0.04 μm for the smaller bacteriophages. Despite their minute size, these micro-organisms are a serious problem in many of the industries using compressed air and gases, because, as living organisms, they are able to multiply freely under the right conditions – and these right conditions are usually the ones involved in the manufacturing process.

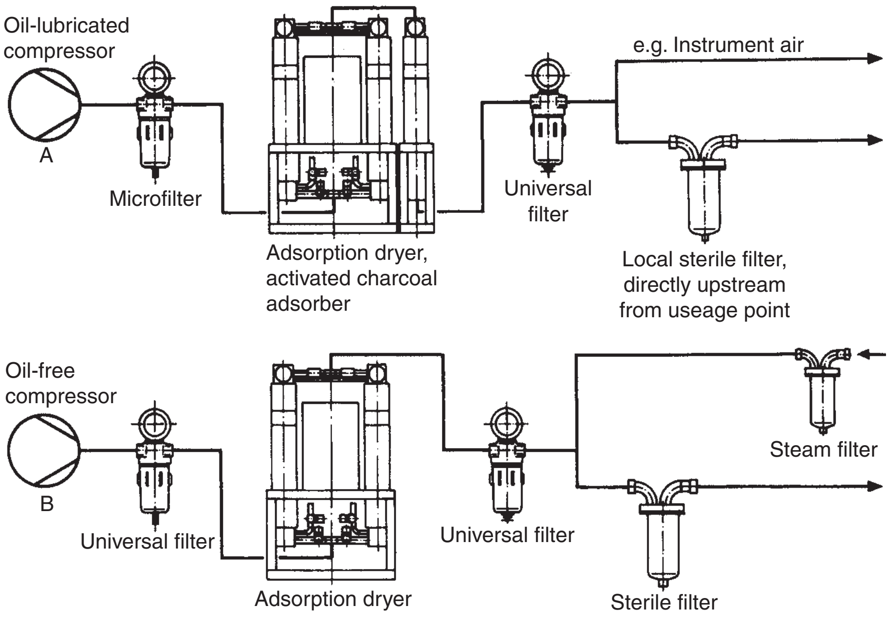


Figure 6.44 Sterile compressed air delivery

Sterilizing filters

In the selection of sterilizing filters for compressed air systems (Figure 6.45), the following parameters should be fulfilled as the:

- filter must not allow penetration of any type of micro-organism that could cause contamination
- filter must be able to operate reliably for long periods
- materials of construction must be inert and not support any bio-growth
- filter must be economically viable, both in terms of initial cost and running costs
- filter must be easy to install, use and maintain
- filter must be able to be integrity tested
- filter must be able to be steam sterilized *in situ* and repeatedly, and
- filter's physical size should be as small as possible so as to minimize installation problems.

Filter medium material for the removal of viable organisms from compressed air tends to be either of borosilicate glass microfibres or meltspun fleece or PTFE membranes, supported on 100% glass fibre woven fabric or polysulphone or polypropylene spunbonded textiles.

A typical binder-free borosilicate microfibre filter can offer 99.99999% efficiency at 0.01 μm, and remain in service for up to twelve months. It would have a two-layer structure. The contaminated air or gas first strikes the outside layer of relatively coarse filter medium (2 μm). This filtration level allows the particles of

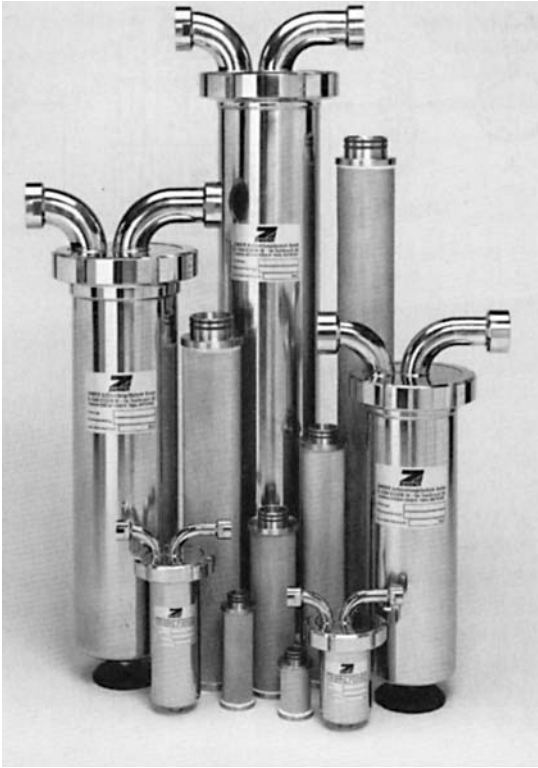


Figure 6.45 Sterile process filters

dirt to be trapped before they penetrate into the microfibre web. This inner layer of microfibre web material traps particles down to a filtration level of 0.01 µm, which is particularly important in holding back any residual aerosol of water or oil.

These two layers of fibrous medium combine together to hold back all of the solid particles. In a dry air stream, they will also hold back bacteria, as long as the micro-organisms have no means of multiplying in the depth of the filter medium. A filter medium that contains a binder material would be considered suspect for this application, as the binder would probably act as a nutrient for bacterial growth.

Membrane cartridge filters are extremely flexible and high in tensile strength. The cartridge construction is based on a multi-layer combination of filter media in pleated format. Those polymers that have been used extensively as filtration media in coarser grades are now widely used as membrane filters. A typical format has a cartridge fabricated from a pleated filter pack, which contains a very fine polyolefin fibre prefilter layer, two nylon membranes of the same pore (0.2 µm) size, and a downstream polypropylene support. The layers of nylon microporous membrane and polypropylene prefilter are pleated together and supported by an inner support core. The end-caps and core are melt sealed in polypropylene.

The medium is a thin (110 μm) microporous nylon membrane, having a controlled pore size. Its homogeneous cast polymer structure cannot release fibres, and no fibrous medium is used downstream of the nylon membrane (to prevent fibre migration). The only materials used in these cartridges are nylon and polypropylene, and because of this construction the cartridges can be autoclaved.

Hollow fibre cartridge

The hollow fibre filter technique was originally developed for dialysis filtration, but has been adapted for a very wide range of applications, including use for the sterilization of compressed air. The main advantage of the hollow fibre format (Figure 6.46) is that the filter has a smaller spread of hole dimensions, but a large filtration area in a given housing volume. Rated retention sizes of 0.1, 0.2 and 0.45 μm are available.

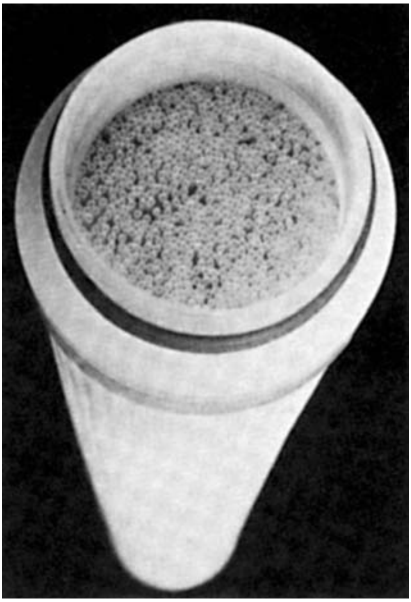


Figure 6.46 Hollow fibre cartridge

Because of the much closer pore distribution than with flat membrane media, the number of pores per unit filter area is far greater, thereby extending the service life of the element. Equally a closer pore distribution means that the largest pore is considerably reduced: a conventional membrane has a maximum pore size at least 0.3 μm larger than that of hollow fibre material. This development of membrane filter elements with a rated pore size of 0.1 μm, a longer service life and a reduced pore size distribution is a considerable aid to safer compressed air and gas sterilization, as this means the ability to retain viruses as well as bacteria.

The construction of the hollow fibre membrane also means that it is economical to manufacture in smaller capacity elements, down to a rated flow of 40 m^3/h at 8 bar for laboratory use or for seed fermentation applications. The hollow fibre membrane, although it is manufactured from 100% polypropylene and is therefore hydrophobic, can be used on liquid applications provided that a wetting medium such as IPA is acceptable.

Sterile filter systems

Sterile filter cartridges must be fitted into a pressure holding housing, the method of sealing being by means of single or double sliding O-ring seals, to allow expansion and movement of the cartridge during *in situ* steam sterilization, and under shock load conditions, without breaking the seal. Compressed air sterilization filter housings need to be designed so as to protect the cartridge as much as possible from undue stresses or flow slugs or contamination, and allow condensate to drain away freely.

Segmented filters are used quite effectively for varying flow requirements for air, gas, compressed air, liquids and steam, particularly in food and beverage applications. For compressed air and other gases, the filters use PTFE flat filter membranes that are hydrophobic and resistant to all commonly used chemicals, making them ideal for aseptic packaging operations, and food and beverage processing duties in general (Figure 6.47).

Figure 6.47 Segmented filter

In a typical application, air or gas flows into openings in the outside of a segment and passes through the filter medium into an adjacent segment. The filtered air or gas then leaves through openings in the centre of the cartridge, and out of the filter housing.

The number of segments and type of filter media used are determined by the application. Each filter segment functions independently and the throughput can be increased by adding segments.

Oxygen filters

Oxygen is a potentially dangerous gas capable of producing violent spontaneous combustion in contact with combustible contaminants such as rust scale and other degradation products in oxygen pipelines, solvents, lubricants, greases and so on. Equally the presence of pure oxygen can considerably lower the ignition temperature of combustible particles. The requirements for oxygen filters are thus stringent and unique, governing material choice and construction of the filter body, choice and form of the filter element, and seals and accessories.

Oxygen filter housings may be made from carbon steel or stainless steel, and require high quality construction and cleaning. Carbon steel parts are preferably fine finished and phosphated. Internal fittings may be of non-sparking bronze alloys with complete electrical loading. The design should also be such as to avoid vortex formation and minimize particle impact (to avoid particle temperature rise) with positive separation of contaminants into a calm region.

Sintered metals are a suitable choice for the filter elements, specifically sintered bronze on a stainless steel internal support. Such filters are capable of providing filtration close to 5 μm. Elements are not regarded as cleanable, but may be recoverable in the sense that the support parts may be salvaged and refitted with new bronze elements.

Oxygen enrichment using membranes is a standard process, although high purity oxygen is not currently produced from air using membranes. Applications for oxygen-enriched air include the chemical and processing industries, steel and other metal industries, and health care. Major users of oxygen-enriched air are in gas-fired furnaces, in aerobic waste treatment processes, and in the medical sector for use by patients with respiratory problems.

The membrane modules used for air enrichment are generally of the plate-and-frame type, based on thin film silicon polymers. An oxygen filter should always be fitted with two pressure gauges, one upstream and one downstream, or alternatively with a differential pressure gauge. Such gauges must be capable of withstanding the maximum static pressure of the system on one side and atmospheric pressure on the other, without damage or losing calibration. Gauges must be thoroughly degreased for oxygen service.

Ultra-pure gases

In the chemical industry, and in the production of semiconductor components, there is a demand for the supply and storage of extremely pure gases. Hydride technology utilizes the properties of special metals and alloys, which absorb hydrogen and are highly reactive to oxidizing gases, but do not react at all to noble gases. Gas purification systems based on the reaction behaviour of the various materials have been developed to eliminate solid particles and foreign gases. The system typically consists of a number of purification stages, able to produce gases with a degree of purity of 99.99999%.

In the first stage of a typical process, ‘technical’ gases, contaminated with oxygen, hydrogen and carbon monoxide, are given a preparatory treatment by catalytic combustion, to convert as much CO and H_2 as possible to carbon dioxide and water. The gases then flow through a dryer, which reduces the moisture to values below 1 ppm.

In a low temperature purification system, the gases are then cleared of all components that, at room temperature, will react with the respective getter alloy. After this stage, the gases only contain components that do not react to metal surfaces at room temperature. The residual carbon monoxide and oxygen contents are lower than 0.1 ppm, and the water content lies below 0.5 ppm.

The gases are then taken through a high temperature getter stage, which reduces the residual foreign gas components, excluding noble gases, to the part per billion range.

With a higher gas flow, a secondary purification of hydrogen can be carried out in alternating hydride storage systems. Since this process eliminates even the inert gas components, all foreign gas components now lie in the ppb range. If the gas is now required to be largely free from particles, it is then led through a combined deep-bed and membrane filter, to filter out particles greater than 0.02 μm.

Sterile filter selection

Sterile filters are normally sized according to the flow rate versus pressure drop information available. For example, a typical fermenter, requiring approximately 1 bar pressure in the compressed air feed to overcome the liquid head, may be supplied with compressed air at 16.5 bar to allow for pipe losses, valve losses and filter losses. When the filter size is being considered, firstly for prefiltration, it is important to know whether it is operating wet or dry. The initial pressure drop across a dry filter should be around 0.07 bar; this could increase to say 0.15 bar if the filter is operating to remove liquid water and perhaps oil. The build-up in pressure drop after this is due to the dirt collecting and gradually blocking up the filter material.

Generally, coalescing-type prefilter elements are designed to withstand very high pressure drops; however, it is normal to replace the cartridges at somewhere between 0.3 and 0.7 bar differential pressure in an air sterilization prefiltration application. Should more than one stage of prefiltration be required, the total pressure loss across all the prefilters should be kept at the same level.

The actual compressed air sterilization filter is also sized to give an initial pressure drop of around 0.1 bar, although as with the prefiltration system, filters can be oversized to reduce this pressure drop or vice versa. However, the cost of extra differential pressure should be borne in mind.

Compressed air sterilization filters must be protected, both from normal compressed air contamination and from contamination contained in the steam used to resterilize them. It is not, therefore, normal to change them due to increased pressure drop, but when their recommended expected life has expired, as is usually stipulated by the number of repeated steam sterilizations they can safely withstand.

Routine steam sterilization is a requirement for any system of sterile filtration, and is often carried out after each batch, according to laid down procedures, although this is not absolutely necessary, provided that the filter is kept pressurized, the relative humidity is kept below recommended levels, and a small bleed of air is allowed to flow continuously. It is important to note that the sterilizing steam must be saturated and free from any additives. Dirt in the system can cause filter contamination and hence increased pressure drop, and additives also have the same effect by crystallizing on the filter medium, which may also concentrate any possible chemical effects.

In general, a well-designed system could give in the region of twelve months' service life before cartridge replacement. The life can, of course, be shorter or much longer than this, but in any case the insignificant cost of the replacement cartridges and their easy replacement makes this of little relevance, compared to the security of the system and the likely impact of contamination.

Validation

Nothing should be left to chance when clean sterile compressed air or gases are required for fermentation, genetic engineering or pharmaceutical drug production. It is essential that any filter used has been previously integrity tested to ensure that it will perform its duty. The best way for the integrity testing of a filter element, and indeed the whole filter, is to use a cloud of test particles at the critical size of 0.1–0.3 μm. Essentially, the test is based on creating an aerosol of DOP (dioctyl phthalate) in the critical particle range, with which the filter is challenged, followed by measuring any penetration with an aerosol photometer downstream. DOP has, however, largely been replaced by other materials because of possible health hazards, and pure corn oil is now used, as are other oils giving the same type of particle size spread when atomized. Typically, some 70% of the aerosol particles generated are less than 0.3 μm, with a total particle size spread of approximately 0.05 to 3.0 μm.

6J. RESPIRATORY AIR FILTERS

Basic non-powered air purifying respirators consist of masks (Figure 6.48), which can be reusable or disposable. They are designed to protect the wearer from solid particles (mildly toxic or irritant) and water-based aerosols. Disposable face masks should preferably be easy to put on, have strong head straps, soft inner face pieces and adjustable nose pieces and they should fit well over the face. The outer shell should be resistant to moisture.

The simple mask is effectively made from a stiff piece of filter medium, and has no separate filter. Respiratory face masks are used in more aggressive industrial environments: the half mask shown in Figure 6.49 incorporates twist in/out main filters and a snap-on prefilter. The mask flexes as the wearer breathes and speaks.

These masks do not protect the wearer against noxious or toxic vapours in the atmosphere. Where people are required to work in such an environment, then normal practice is for the wearing of a hood, connected to a compressed air supply, carrying air purified to respiratory air standards. The purity requirements for compressed air used for respiration and hygienically critical applications such as hospital patient recovery,

Figure 6.48 Simple face mask

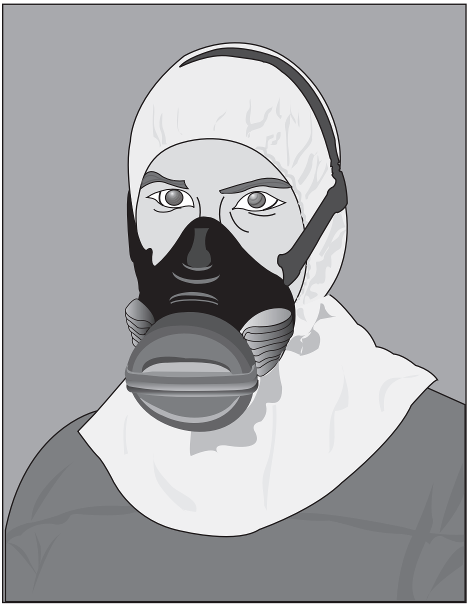


Figure 6.49 Half mask respirator

and life support in hazardous environments, such as mines, underwater tanks, etc. must be free of toxic or irritating ingredients, odours, dust and other solid particles.

Most standards organizations around the world have established suitable standards pertaining to the purity of compressed air for human respiration, such as BS/ EN 12021:1999, with quite stringent regulations. For example, NIOSH 42 CFR Part 84 defines nine classifications of non-powered air purifying respirators. Although variations in requirements exist, primarily due to the method and type of application, most existing specifications and standards are in substantial agreement.

The most common method of producing compressed air for human respiration is by the compression of normal atmospheric air. Compressors used for this purpose may be of rotary or centrifugal, coaxial screw, piston or diaphragm type. The choice of compressor will depend on the pressure at which the air is to be used and the volume rate of air delivery required.

Generally, in low pressure (6–7 bar) industrial systems, the breathing air supply is tapped directly from the working compressed air line. This places a premium on the correct air line installation, even though the breathing air is separately filtered. Figure 6.50 shows a typical layout where personnel are engaged in work requiring breathing air and pneumatic tool supplies. With all compressors, the main requirement is that they should be installed so that they can only induct clean and uncontaminated air as far as possible.

The minimum delivery requirement for breathing air is 120 l/min of free air per person, with a higher figure desirable. Pipelines, filters and pressure reducing valves must

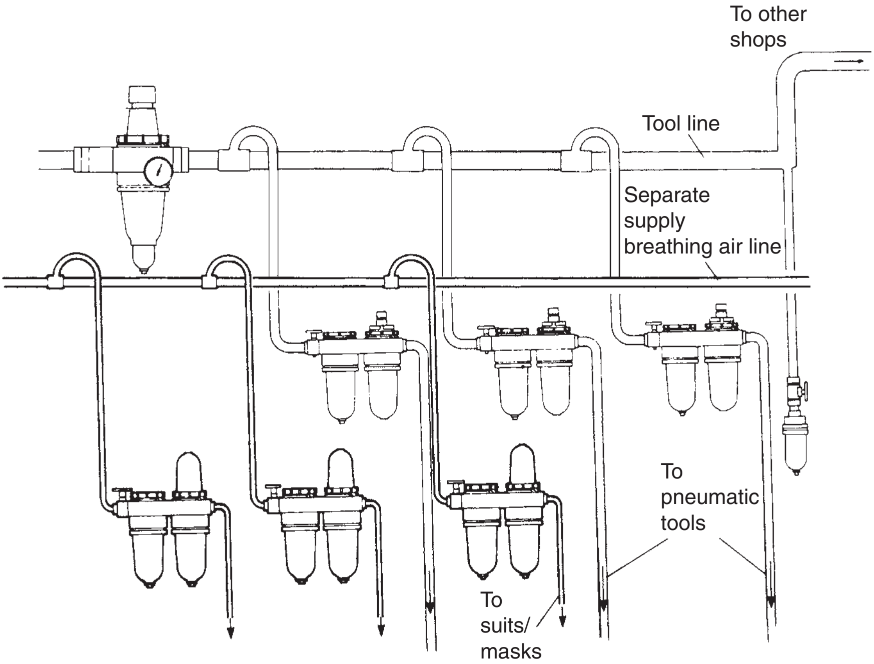


Figure 6.50 Working and breathing air supplies

be sized accordingly. The relative humidity of the air should be between 24 and 80% at atmospheric pressure. The acceptable temperature for breathing air is between 15 and 25°C. The humidity requirements largely rule out the use of a dryer in the system, although a humidifier may be included in the breathing air system if a dryer is essential for other purposes: continual breathing of dry air can cause discomfort or respiratory problems. Certain types of air line lubricators can be used as humidifiers if necessary. Cooling equipment may be necessary to meet the temperature requirements.

Contaminants

The problems of contamination of breathing air largely echo those already described in the treatment of working supplies of compressed air, with perhaps greater emphasis on gaseous impurity removal, especially carbon monoxide.

Oil aerosol or oil vapour is present in atmospheric air as an airborne effluent from industrial processes and exhaust emissions. Lubrication in compression chambers invariably means there will be oil aerosols or vapour present in the output from the compressor.

Oil vapour content is dependent mainly on the discharge temperature and the chemical additives used by oil suppliers. Oil vapours may condense to some extent in down line pipework, but will almost certainly be present as a gaseous form at the point of application, if it is not removed by prior adsorption. Ultra-high efficiency filters are required for oil mist removal, i.e. those with an efficiency in excess of 99.9999% (at 0.01 μm).

Dirt particles are present as rust scale, pipe debris, atmospheric pollution, wear in the compressor, and carbon present as unburnt hydrocarbons. This particulate matter must be removed, using similar filters to those described in Sections 6G and 6I.

Water vapour, from a physiological standpoint, is not necessarily injurious at the relative humidity figures quoted earlier, but its effect upon the equipment in the breathing air system, particularly valves and cylinders, may be quite harmful. This is where it may be best to dehumidify the air to a dew point below 0°C at atmospheric pressure, and then rehumidify at the points of breathing use.

Carbon monoxide is perhaps the most insidious danger faced by compressed air users. As a contaminant of compressed air, carbon monoxide is usually introduced through the intake port of the compressor. The compressor power drive itself, with exhaust fumes from oil, gasoline or gas powered engine, without adequate venting, can be a major source of carbon monoxide. The toxicity of carbon monoxide is due to the fact that the carbon monoxide molecule has an affinity 300 times greater for the haemoglobin molecule than does oxygen. At levels of only 2% carbon monoxide-haemoglobin involvement in the bloodstream, serious disturbances to the human psychomotor functions can occur, but this disturbance does not normally become significant until 5% involvement levels are reached. At elevated pressures, however, absorption may be more rapid and complete, and any consequent impairment to higher psychomotor functions may be disastrous.

A 2% involvement corresponds to about 10 ppm of carbon monoxide, so it should be readily appreciated that adherence to the air purity standards is absolutely essential (these call for CO contents of 5 ppm).

The difficulty in removing carbon monoxide from the air is due to its physical and chemical properties. It has a low boiling point and critical temperature, and hence is not readily adsorbed. It is almost total insoluble in most solvents and consequently cannot be easily removed by absorption. The main practical method for the effective removal of carbon monoxide at most temperatures utilizes catalytic oxidation (to carbon dioxide). Catalysis is the process in which a chemical reaction is initiated or accelerated by the presence of a catalyst, which is a material that induces a chemical reaction but which itself is unaltered during the reaction. The type of catalyst that has proved most useful for the removal or elimination of carbon monoxide, by the oxidation to carbon dioxide, is generally known as a hopcolite.

Because catalysts in general, and hopcolites in particular, are quite sensitive materials, certain precautions must be observed to ensure the required performance. It is essential that liquid and solid particulates, as well as vapours, be filtered from the air stream prior to the hopcolite, because the catalyst material is very susceptible to poisoning by the adsorption of contaminants onto its active centres. Water vapour in particular exhibits strong poisoning characteristics for hopcolites, so, to ensure a reasonable catalyst life, the compressed air must be ultra-dried by the use of desiccants.

Since the effectiveness of hopcolites is so actively limited by moisture that it requires protection by desiccants, it has become common practice to assume the catalyst to be inactive when a certain level of relative humidity of the air is exceeded. For this reason, some systems utilizing a hopcolite filter include a colour change indicator based on a moisture sensitive material. This type of indicator is, in fact, a safety device and measures air moisture content, not carbon monoxide content. Periodic testing for carbon monoxide in the cleaned air is therefore warranted where hopcolite filters are employed.

Carbon dioxide is present in the atmosphere in varying concentrations, depending upon the environment. It may be tolerated at much higher levels than carbon monoxide, but again it will impair psychomotor functions if levels are too high. Carbon dioxide is readily removed by a variety of sorbents, both absorptive and adsorptive, with the absorptive type predominating. (The economic removal of carbon dioxide from atmospheric air is a problem currently attracting a great deal of attention, as it may offer one method of countering global warming.)

Nitrous oxide and nitrogen dioxide gases are present in compressed atmospheric air as effluents from industrial processes and also from combustion in the compressor. They are irritants to the respiratory passages and can be detected in very small concentrations. Their removal is not easy. Chemical, catalytic or selective absorption means must be utilized to eliminate these impurities.

Odours are not necessarily a problem when the compressor is correctly sized, cited and maintained. However, it does not take much odour in the inlet air or created in the compressor system to produce an offensive situation in a breathing hood. The most effective and common approach to odour removal is the use of activated carbon as an adsorbent. Activated carbon filter elements have a limited effective life and need replacement at regular intervals, depending on the concentration of odorous gases that they have to adsorb, but the carbon is relatively easily regenerated.

Packaged systems

Several complete packaged purification systems are available that take untreated compressed air and purify it to the highest air purity standards. Purification systems are available for both high and low pressure use.

Systems in use include five- and six-stage treatment units, removing oil and water aerosols, carbon dioxide and acid gases, solid particles, oil vapours, odours and flavouring substances, and carbon monoxide. Typically, a good system should provide about 600 operating hours on chemical adsorption filters and up to 3000 hours for depth filters.

The modular system shown in Figure 6.51 has been designed specifically for use where both carbon monoxide and carbon dioxide removal is necessary. In operation,

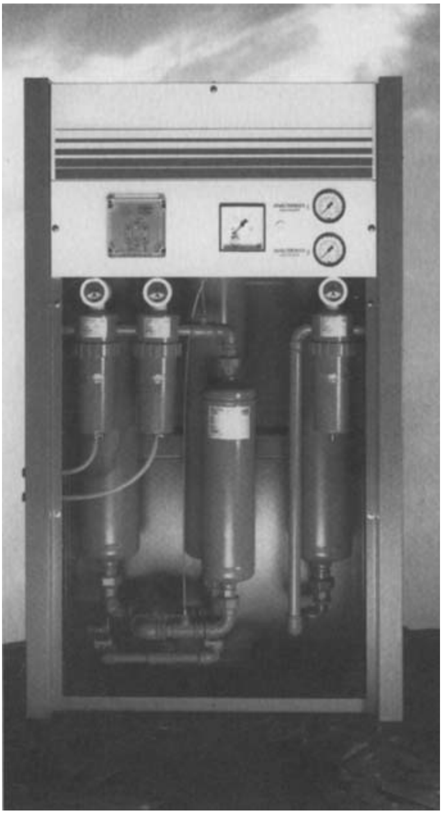


Figure 6.51 Modular breathing air system

air from a compressor passes through micro- and submicro-filters, in which solid particles and oil and water are removed to give a residual oil content of 0.01 mg/m^3. A timer controlled solenoid valve removes the resultant condensate. The compressed air then passes through an absorber, reducing carbon dioxide content to 300 ppm. Moisture is extracted in a dryer, while oil vapours and hydrocarbons are removed in an activated carbon bed. The carbon monoxide content of the air is reduced to around 5 ppm in an oxidation stage, and finally the air passes through a dust filter to remove any abraded particles produced during the adsorption and oxidation stages.

Portable versions of these packaged systems are available for industrial use, as well as use by the emergency services. Whatever system is relied upon for providing high purity air for breathing purposes, it is fundamental to the safety of the user that the specified system be capable of providing air quality of a consistently high standard, under varying environmental, and often arduous, conditions. Product integrity, quality assurance and verification are essential characteristics of any form of breathing air equipment.

7

OTHER TYPES OF SEPARATION EQUIPMENT

SECTION CONTENTS

7A. INTRODUCTION

The bulk of this Handbook, appropriately, considering its title, has been devoted almost entirely to the technology of filtration, although other forms of separation have been touched on in various places. This section now aims to cover all non-filtration forms of mechanical separation.

The achievement of a separation of two or more distinct phases – what is termed mechanical or physical separation (although neither word is precisely descriptive) – can be managed by one of two major technologies:

- filtration (by entrapment in or on a barrier that permits passage of species smaller than a certain size and retains the rest – this is separation by means of relative particle *size*), and
- sedimentation (by settling of particles in a mass of fluid – this is separation by means of relative particle *density* – although particle size plays a part as well).

The division between these two technologies is usually quite clear, although some processes use both together, and other phase separation processes are only just able to be included under one or other of these headings.

It must be remembered, when words like ‘separation’ and ‘phase’ are being used, that there is a whole host of other phase separation techniques, which are neither filtration nor sedimentation. These are the phase-change processes, such as distillation, absorption, extraction and so on. However, in the prime context of this Handbook, which is the removal of contaminants from fluid flows, these phase-change processes have little or no part to play.

The present section is therefore largely concerned with sedimentation: the separation of liquid droplets or solid particles from a suspending fluid, by allowing them to settle out of suspension under the influence of gravity or of centrifugal force. There is a tendency to regard the division of mechanical separation processes as between filters and centrifuges, whereas the correct split is between filters and sedimenters, because centrifuges, according to their design, are able to separate either by filtration or by sedimentation (or, in the case of the screen-bowl decanter, by both).

A further complication of which one must be aware concerns the word ‘separator’, which can mean several different things. The dictionary definition: ‘a device for separating things into constituent parts, as milk into cream, etc.’ does not help much. In the previous editions of this Handbook, the term covered centrifuges, cyclones, wet scrubbers, coalescers and hydrostatic precipitators – a somewhat eclectic mixture, which, most surprisingly, excluded all kinds of gravity sedimentation equipment. To many practitioners of ‘filtration and separation’ (itself a tautologous phrase) a separator is most likely to be a gravity settler, while to the centrifuge manufacturer it is a disc-stack centrifuge (‘high speed separator’).

This is clearly a word to be used with care in any filtration and sedimentation context. It is used in this Handbook only in the general sense when unmodified, so that the term ‘separator’ means any form of physical separation equipment. The term only has a specific meaning when preceded by a modifier: ‘magnetic separator’, ‘lamella separator’, or, as is mainly the case in this section, ‘gravity separator’ or ‘sedimenting separator’.

Sedimentation theory

The theory of filtration is largely concerned with the size and shape of the separating medium, with the way in which particles are trapped by the medium (at its upstream surface or in its depth), and with the way that a cake of trapped solids builds up on the medium. By contrast, the theory of sedimentation is entirely concerned with the way in which a particle (or droplet) settles in a continuous fluid. The design of sedimentation equipment is then a matter of giving the particle enough time to settle out of suspension, either to the bottom of the settling tank, or to the nearest solid surface (e.g. to the nearest one of an array of parallel plates).

If a particle falls in a large expanse of fluid, it accelerates downwards under the influence of gravity, and it is held back by the drag force exerted on the particle by the fluid. As the downward velocity increases, so does this drag force, until a velocity is reached at which the gravity and drag forces are equal, after which the particle no longer accelerates downward but instead moves at constant speed – the *terminal velocity*.

The terminal velocity is calculated from the formula derived from Stokes' law, which gives this velocity as:

- directly proportional to the square of the particle diameter
- directly proportional to the relative density of the particle (the difference between its density and that of the fluid), and
- inversely proportional to the viscosity of the fluid.

To a first order of approximation, the terminal velocity can be calculated from Stokes' law, but as soon as other particles get close to the one in question, they start to affect its falling velocity, and the flow regime changes to what is called *hindered settling*. The settling calculations then become much more complicated, although the effect can be seen as equivalent to a large increase in the fluid viscosity.

It will readily be seen, from the form of Stokes' law, that sedimentation in a solid/fluid system can be used:

- to separate solids from fluids, because of the density difference, and
- to separate two or more solids, one from the other, because of their different rates of settling caused by different densities or different particle sizes.

The first of these separations is termed clarification, because it is usually a classification of the fluid that is the goal of the process. The second is termed classification, because the goal is the separation of the suspended solids into two or more fractions (by size or density).

The relationship between particle density, particle diameter and fluid viscosity, governing settling velocity, holds true as long as the particle size is not so small that its motion is affected by Brownian movement. This is the net out-of-balance force of the collision of the molecules of the fluid on the particle. For large particles the collisions even out all round, but for very small ones they do not, and small irregular movements of the particle can be seen. Where Brownian movement is occurring, the terminal velocity can be substantially reduced and, at a certain particle size, Brownian movement is sufficient to keep the particles suspended indefinitely. This may be taken to be the case with particles of one micrometre or smaller in air.

The relationship also applies strictly to a fluid in a perfectly static condition. Fluid movements, which produce local vertical velocities, will affect the falling velocity of particles accordingly. With pure translational velocity, the effect of fluid velocity can be neglected, although absence of vertical velocities is only likely to occur with laminar flow. With turbulent flow, conditions are indeterminate, except by truly practical tests.

The significance of the aforementioned is that settling can be used as a method of separating solid particles from a fluid, provided that the terminal velocity of the particles is high enough for the particle to settle out, in the time that the parcel of carrier fluid takes to pass from the entry to the discharge of the separating device. The design of clarifiers and settlers must ensure that this is so.

The settling rate may be increased by artificial means, such as deliberately introducing a vortex motion in the fluid. The increased G-force applied to the particles increases their velocity relative to the bulk of the fluid. This principle is used in simple vortex flow separators, as well as in centrifuges and cyclone separators.

Another method of producing increased settling rates, without introducing motion in the carrier (and thus consuming energy) is to cause the particles to agglomerate and thus increase their effective diameter. This effect can be considerable, since terminal velocity is proportional to the square of the diameter. Thus an agglomeration that increases the effective diameter ten times will increase the settling rate by 100 times. This is the principle employed in ultrasonic fluid cleaners and separators, in which the ultrasonic waves promote agglomeration of any particles suspended in the fluid. It is also, of course, the way in which mechanical separators are made to work more effectively, by the use of chemical or physical coagulants.

Of the contents of this section, 7B (Sedimenting Separators), 7C (Centrifuges) and 7D (Cyclones and Hydrocyclones) are solely concerned with sedimentation, 7E (Coalescers), 7G (Mist Eliminators) and 7H (Electrostatic Precipitators) are largely so, but 7F (Wet and Dry Scrubbers) is as much concerned with filtration as well.

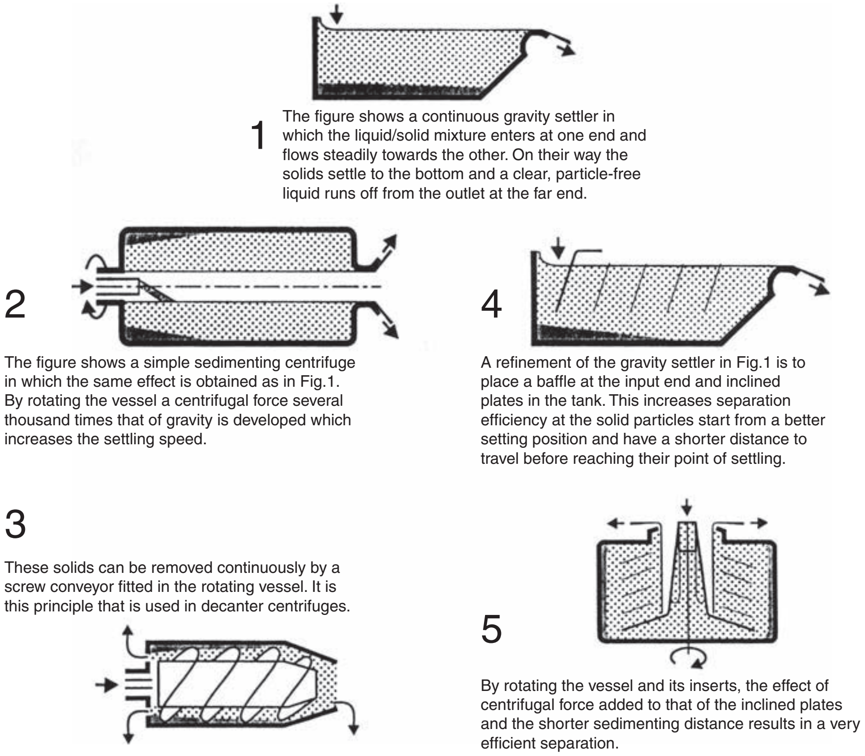
7B. SEDIMENTING SEPARATORS

Physical separators that work by sedimentation are of two main types: those working under the influence of gravitational force alone, and those using centrifugal force, either in a mechanically driven centrifuge (Section 7C) or in an inertially driven cyclone or hydrocyclone (Section 7D). Gravitational separators, in turn, have two main design forms: those with large circular or rectangular basins through which the liquid flows, in a time sufficiently long for the separation to occur, or those using arrays of parallel plates or tubes to give a shorter settling distance, and hence a shorter settling time to achieve the required separation.

The main types of sedimenting separator are described in Figure 7.1, which shows five different separators, two of which (illustrations 1 and 4) are gravity driven, and the other three (illustrations 2, 3 and 5) are centrifugally driven. No means are shown in Figure 7.1 for the removal of separated solid from the gravity separators, nor is solid removal included in two of the centrifuge designs (2 and 5).

Gravity separators

The simplest form of practical gravity separator, a clarifier, is shown schematically in Figure 7.2. It takes the form of a large tank, in this case a cylindrical one, which receives its feed suspension at the centre of the tank. The water flows radially across the tank and out over a weir at the periphery, into a collection trough.



1 The figure shows a continuous gravity settler in which the liquid/solid mixture enters at one end and flows steadily towards the other. On their way the solids settle to the bottom and a clear, particle-free liquid runs off from the outlet at the far end.

2 The figure shows a simple sedimenting centrifuge in which the same effect is obtained as in Fig.1. By rotating the vessel a centrifugal force several thousand times that of gravity is developed which increases the settling speed.

3 These solids can be removed continuously by a screw conveyor fitted in the rotating vessel. It is this principle that is used in decanter centrifuges.

4 A refinement of the gravity settler in Fig.1 is to place a baffle at the input end and inclined plates in the tank. This increases separation efficiency at the solid particles start from a better setting position and have a shorter distance to travel before reaching their point of settling.

5 By rotating the vessel and its inserts, the effect of centrifugal force added to that of the inclined plates and the shorter sedimenting distance results in a very efficient separation.

Figure 7.1 Types of sedimenting separator

The suspended solids separate from the water and fall to the bottom of the tank, in which they move to the centre because the bottom is in the form of an inverted cone, and the solids slide down the sloping walls of this cone. They are assisted in this movement towards the centre by a set of vanes that turn on a centrally mounted shaft, turning slowly so as not to resuspend the separated solids. The solids flow out of the clarifier as a thick sludge through the underflow pipe, which has an integral flow control device to stop water leaving as well.

The gravity clarifier may also be rectangular in plan, with the water flow from one short side to the other, along the length of the clarifier. The floor of the tank slopes downwards towards the feed end of the contaminated water, where the underflow pipe is situated, and such a clarifier usually has a set of rakes running across the bottom of the tank, parallel to the short sides. These rake blades are mounted on chains that drag the blades slowly along the tank bottom, in turn scraping the accumulated solids towards the underflow, where the blades are lifted up and returned to the other end of the tank. This kind of clarifier has been much used in the treatment of fresh water.

The gravity clarifier aims to remove as much solid as possible from suspension in the liquid, and to produce a solid underflow that is as fully dewatered as is possible

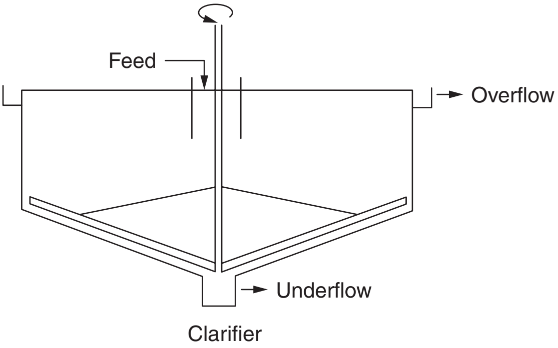


Figure 7.2 Simple gravity clarifier

considering that it is coming out of a supernatant layer of liquid. An alternative use of the gravity settling device is to produce a more watery sludge, when the function is termed thickening, and the device is termed a gravity thickener. An example of this use is the thickening of a suspension that is wanted for further processing in that state, or to reduce the dewatering load on a subsequent process that will yield a very much more thoroughly dewatered mass of solid – ahead of a centrifuge, for example.

There are two major improvements on the basic clarifier design. The first involves the addition to the feed suspension of flocculating agents, which are chemicals that act to bind the particles in suspension to one another, forming flocs of much larger diameter, and so a much faster settling velocity in the settling tank. Floc formation takes a finite time so the addition point for the flocculant is somewhere in the feed line to the settling tank, depending on the nature of the solids in suspension, the nature of the flocculant, and the design of the clarifier. Addition may occur in the feed zone of the clarifier itself, or in a flocculant addition tank, with mixer, upstream of the clarifier.

The other major variant is to fit the settling tank with a solids removing rake mechanism. This is easier done with a rectangular tank, but it is also possible with a circular vessel. The rake blades move a short distance forward, then are pulled up out of the layer of solids and returned to their starting position. This motion intentionally causes local liquid turbulence and some resuspension of the solid, the result of which is to achieve effective separation of the solids into two fractions – one left in the bottom of the tank for separate removal, and the other raked up out of the pond, where it can be washed if necessary. This is the basis of the gravity classifier, much used in the mineral processing industry.

Lamella separator

The gravity separator enables a particle to settle out of suspension into a layer of separated solids formed at the bottom of the settling tank. The particle can also be considered to have separated from suspension if it can be encouraged into contact with any continuous surface over which the liquid is flowing. This is the operating principle of the lamella separator, in which a number of continuous surfaces (usually flat plates but also corrugated plates or tubes) are arranged in a parallel array, as exemplified in Figure 7.3. The lamella separator is a gravitational sedimentation device, fitted with a set of plates or tubes, joined parallel to one another, and with the whole set tilted at an angle to the horizontal. The presence of the plates in the suspension flow stream gives a very short settling distance (for a suspended particle or liquid droplet) before it hits a solid surface, and so leaves the suspension. The effect of the plates is thus to provide a very large area for sedimentation within a relatively small ground area.

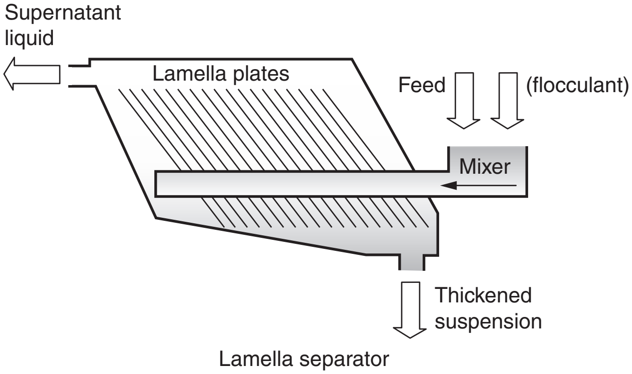


Figure 7.3 Lamella separator

The vertical distance between the plates varies from a few millimetres to a few centimetres, depending upon the size of the particles to be separated, and upon the required flow conditions. Separated solids can slide back down the plates and leave at their lower ends (which risks their re-entrainment at the entry points) or they can be carried on and discharge over the top edge. (The angle of inclination of the plates must, of course, be greater than the wet angle of repose of the solids.) The clarified liquid is discharged through special rising channels.

Lamella separators can be used as liquid/liquid separators (as in oil-water separation – discussed at some length in Section 5C), or as clarifiers, for the removal of small amounts of suspended solids – an application of increasing use in water treatment. Liquid/liquid separation and solid removal can also be achieved in the one separator. The device can, in addition, be used as a thickener, in which case there will be a sludge collection space below the plate assembly, which must be deep enough to allow the formation of a sludge compression zone.

Flotation

A completely different sedimentation process reverses the normal settling method by making the particles or droplets less dense than the suspending liquid, so that they float to the top of the liquid, from where they can be skimmed off as a thick layer. This is achieved by attaching a small bubble of air to each particle, small enough to be able to approach the particle and adhere to it, but large enough so that the combined particle/bubble pair has a net specific gravity of less than unity.

> *[Note: This is the main present meaning of the term, although it originated in the mineral dressing industry to mean literally the floating of particles on a dense liquid medium, with the gas bubble version known as froth flotation.]*

It is obviously essential that the particles, once brought to the surface, do not break away from their supporting bubbles, which is to say that the froth at the surface must be stable. Frothing agents may be added to the suspension to ensure such stability.

There are several types of flotation process, dependent mainly on the way in which the gas bubble flow is generated. In dispersed air flotation, the gas bubbles are produced by means of sparge pipes at the bottom of the flotation chamber, with rows of very fine holes, through which air is forced at quite high pressures. A quite different process, electroflotation, generates the bubbles at the two electrodes of an electrolytic cell. Probably the most common variant, dissolved air flotation (which is normally granted the acronym DAF) uses a supplementary chamber in which air is dissolved in water at high pressure, in which air is reasonably soluble. This air-laden water is then injected into the flotation chamber, whereupon the sharp drop in pressure releases the contained air as a mass of fine bubbles.

Although originating in the mineral processing sector, flotation is now widely used in wastewater treatment, for the removal of residual amounts of suspended solids.

Floc blanket clarifiers

Occupying a position between sedimentation and flotation are the floc blanket and adsorption clarifiers, in which a layer of material is kept suspended (by fluidization) in an upward flow of water carrying solid particles. This flow is dosed with coagulant, so as the water flows through the blanket, the particles grow and are held in the blanket, which thus increases in size, until some is withdrawn for disposal or further treatment.

In the floc blanket version, the blanket consists just of flocculated particles, whereas in the adsorption clarifier, the flocs are attached to granular plastic media. These clarifiers are used for raw water treatment.

7C. CENTRIFUGES

Of the other types of separator, centrifuges predominate, particularly because of the flexibility of their operating principle, in adapting to specific process materials, volume and separation requirements, when they may be specifically described by duty such as separators, purifiers and clarifiers. It must be remembered that the centrifuges about to be discussed are those working by means of sedimentation, and that there is a large range of centrifuge types that work by filtration – which have been described in detail in Section 3I. Almost all sedimenting centrifuges work to achieve clarification of a liquid (or the separation of two immiscible liquids), but, unlike most other clarifying devices, they can do so from a quite concentrated suspension.

The key feature of the sedimenting centrifuge is that it provides the equivalent behaviour of a settling tank, but with much greater settling force – or it is equivalent to a very large settling tank in a small space. The same factors apply as from Stokes' law, namely that the settling rate for a given particle in a given liquid is proportional to the relative particle density, and to the square of the particle diameter, and inversely proportional to the liquid viscosity, but now there is an extra factor to be considered: the centrifugal acceleration. This is given by the product of the radius of the centrifuge bowl and the square of the angular (or rotational) velocity ($r\omega^2$), with the settling velocity now directly proportional to this variable factor, rather than the constant acceleration of the gravity settler.

It is customary to describe the power of a sedimenting centrifuge in terms of the ratio of this acceleration factor to the gravitational acceleration, called the G-force:

$$G = r\omega^2/g$$

or

$$G = 0.011rn^2/g$$

where n = number of bowl revolutions per minute. In the case of a relatively small centrifuge, 600 cm in diameter, rotating at 3000 rpm, G is 3028 – so gravity is being improved on by a factor of 3028 to 1.

[Note: To be more correct, the radius factor in this relationship is actually the distance from the axis of rotation to the position of the particle at any instant, so that, as the particle moves outwards from the centre towards the bowl wall, the centrifugal force acting on the particle increases in proportion to that distance.]

The sedimenting centrifuge

Gravity clarifiers work by providing separation by settlement, the principle being that suspended solids will separate out of the liquid under gravity given sufficient time, although the time required may be unacceptably long. Where continuous through-flow is also required the design of the settling tank must promote hydraulic conditions consistent with high clarification efficiency, and this leads to considerable variety in detailed design. By replacing the gravity clarifier with a centrifugal one, the slow separations, needing very large clarifiers, can occur quickly, in a relatively small piece of equipment.

The sedimenting centrifuge consists basically of a bowl mounted on a shaft that is rotated rapidly, driven by a motor either directly attached to the shaft, or connected to it through a gear box, drive belts and so on. The bowl has one of a number of different shapes, either roughly cylindrical or roughly spherical, and is fully enclosed except for an entry point for the feed suspension, and controlled discharge points for the separated phases. The bowl is enclosed in a casing that controls and directs the final exit of separated liquids and solids from the centrifuge.

The centrifuge is primarily a device providing a mechanical acceleration field through centrifugal force, which can thus separate solid particles suspended in a fluid of lower density. This is similar to the action of separation by settlement in a gravitational field, but very much more rapid, since the mean centrifugal acceleration generated in centrifuges is of the order of 5000 to 8000 times greater than that due to gravity. Centrifuges are also widely used for separating two immiscible liquids, often in the presence of solids.

With settling velocity, and hence performance, directly proportional to bowl diameter and angular velocity, it would appear that ever larger bowls rotating ever faster would yield an ever improving separation performance. However, these same factors directly impinge on the mechanical stressing of the rotating bowl. The bowl stress is made up of two components:

- stress due to the rotation of the bowl’s own mass, and
- stress due to the mass of liquid in the bowl.

Both of these factors are also proportional to bowl size and rotational speed, so that the design of a centrifuge is dependent on the permissible stressing of the rotating system. With smaller bowls, the bowl rotation accounts for about half of the total stress, but becomes increasingly significant with increasing bowl size. The liquid pressure is dependent on the pond depth, and hence on the bowl radius, and may exceed 100 bars (10 MPa). Thus bowl shape and size, rotational speed and choice of bowl material are the primary design parameters.

These considerations have led to the development of three basic bowl shapes for centrifuges that are going to be used for a sedimentation process. These are:

- the roughly spherical bowl, which contains a disc stack that provides a set of parallel spaces, within which the separation occurs
- the short vertical cylinder, whose height and diameter are about the same – this has two basic versions, the imperforate basket and the chamber bowl, and
- the long horizontal or vertical cylinder, whose length is several times its diameter, and which also has two basic versions, the tubular bowl and the much larger, scroll discharge, decanter design.

The first sedimenting centrifuge was a liquid–liquid separator (cream from milk), accepting the presence of suspended solids as an irritant, requiring that the operation be stopped from time to time, and the bowl be cleaned manually. Over the 120 or so years of its life, the sedimenting centrifuge has progressed to being a major processing tool, now able to handle quite thick suspensions, non-aqueous liquids, vapour producing suspensions, all with continuous operation and easy solids handling.

In many cases it is advisable to separate excess liquid prior to centrifugal drainage.

The more important devices used for this purpose are hydrocyclones, sieve bends (curved screens) and gravity thickeners, the first two being particularly attractive because of their simplicity and small size.

Tubular bowl centrifuge

The simplest of the sedimenting centrifuge designs, the tubular bowl centrifuge has a large tube as its separating device (Figure 7.4), with a driving shaft at one end. This design of centrifuge is intended for the separation of immiscible liquids, most notably in the refining of animal and vegetable oils, and the manufacture of soap.

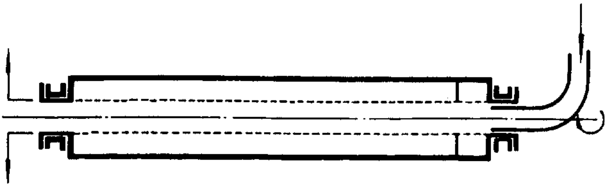


Figure 7.4 Tubular bowl centrifuge

The feed mixture enters the bowl, which is rotating at high speed (which it can do, because, in centrifuge terms, the bowl diameter is quite small), and the two liquids separate as they flow along the bowl. The heavier liquid (usually an aqueous phase) moves to the bowl wall, and the lighter (usually organic) liquid makes a layer nearer to the bowl axis. At the end of the bowl opposite to the feed point, the separated liquids leave the bowl at two different distances from the bowl axis, usually through peeler discs (centripetal pumps) that retain the centrifugal energy as pressure in each liquid.

In their liquid–liquid separation duty, the tubular bowl centrifuges can operate without stopping, but there is always a small amount of solid particulate suspended in the liquids, which is denser than either, and so settles to the bowl wall, where it stays until the centrifuge operation is stopped, and the machine is dismantled for manual cleaning.

The tubular bowl would make a good clarifying device for a single liquid, but the disc-stack centrifuge is more efficient for this purpose.

Imperforate basket centrifuges

A sedimenting centrifuge is formed if the drum-shaped perforated basket centrifugal filter, described in Section 3I, is run instead without any perforations in its bowl (basket) walls. Its behaviour mirrors that of the tubular bowl centrifuge, with feed entering below a lip at the top of the bowl, separating liquids forming two layers as they flow down the bowl, to overflow at the bottom from two levels. As with its perforate basket equivalents, the basket can be under driven or over driven, and can have a three-column suspension.

This is not a very widely used version of the sedimenting centrifuge range, but has a place, especially in some mechanical manufacturing workshops, because it can remove and hold a higher concentration of solids.

Chamber bowl centrifuge

The chamber bowl centrifuge has a drum-shaped bowl, rotating about a vertical axis, within which are several concentric baffles, creating annular compartments, through which the feed liquid flows in succession (Figure 7.5). This is a liquid clarifying device. Alternate baffles are attached to an upper plate so that they can be lifted out of the bowl in one piece, leaving the remaining baffles still attached to the bottom of the bowl. Each baffle has a lip at its discharge end, over which the liquid flows to fall onto the next outer baffle. This lip retains a pond of liquid within each compartment, within which some of the suspended solid particles also separate, to be retained on the baffle surface.

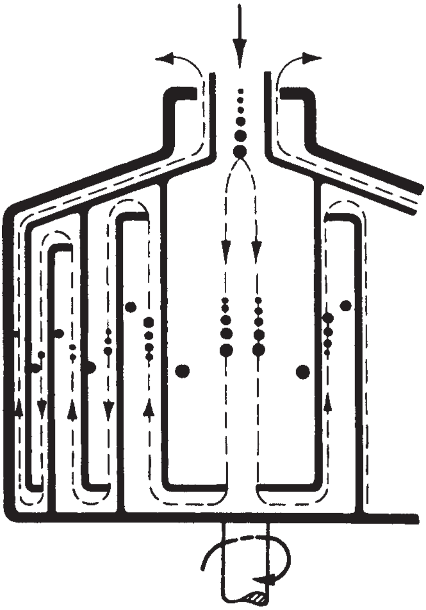


Figure 7.5 Chamber bowl centrifuge operation

The liquid layer thickness diminishes from chamber to chamber, the further each chamber is from the bowl centre: greatest in the central chamber and smallest in the outermost chamber. Hence the effective settling distance also declines from the central chamber outwards. The effective centrifugal acceleration field increases from chamber to chamber (being proportional to baffle diameter), so that with a given difference in densities and a feed liquid of a constant viscosity, the coarser solid particles will separate out in the inner chambers and the finer particles in the outer chambers. Thus the solid matter is classified to some extent, at the same time that the liquid is being clarified.

The clarification efficiency of a chamber bowl centrifuge is influenced by several factors, which can be divided into three groups:

1. the factors affecting the rate of settling, such as particle size, relative densities and liquid viscosity (if the feed liquid contains solid particles of different sizes and densities, the smaller and less dense particles are deposited last);
2. machine design factors, such as the strength of the centrifugal acceleration field, the number of chambers and the liquid layer thickness, and also the height (length) of the chambers (this last dimension cannot be increased arbitrarily because the ratio of bowl outside diameter to bowl height must not fall much below unity, in order to ensure good balancing and good operation);
3. the rate of axial flow in the chambers, which obviously governs the centrifuge output (the greater the throughput, the higher the axial flow rate in the chambers, therefore the shorter the time available for a particle to cover the necessary settling distance – with a lower axial flow rate, the retention time is longer and the clarification efficiency is better).

The specific advantages of centrifuges with a chamber-type bowl include:

- clarification efficiency remains consistently good until the baffle-created spaces become nearly filled with separated solid matter
- large solids handling capacity, hence liquids containing relatively high proportions of solid matter can be processed (especially in two-compartment bowls), and
- the collected solids form a compact cake, hence there is hardly any liquid loss at the end of a cycle.

The disadvantage of this type of centrifuge is that it operates batch-wise, and when the solids spaces are filled with solids, the centrifuge must be stopped and cleaned manually, although this process is helped by the fact that half of the baffles can be lifted out from the bowl when the bowl cover is removed.

Disc-stack centrifuges

The disc-stack bowl contains a large number of conical discs, with a suitable wall thickness to provide sufficient rigidity, spaced at intervals of 0.4 to 2 mm apart (vertically) depending on the liquids to be processed and the consistency of the solids to be removed. Each space between adjacent discs forms an individual centrifugation zone. The liquid entering the feed distributor at the centre of the bowl is thus split up into many thin layers, so that the settling distance of a particle or liquid droplet is therefore made very small. The separating efficiency is thus high even at low bowl speeds, and high speeds with their resultant extremely strong acceleration fields are available.

The angle of tilt (half-cone angle) of the discs is limited by the angle of repose of the solid matter removed, as it is in the wet state and under the influence of the centrifugal force. (The half-cone angle is the angle between the disc and the vertical axis as shown in Figure 7.6.) To enable the solids to slide down the underside of the discs, the angle of the discs to the horizontal must be smaller than the angle of repose of the solids in the centrifugal field.

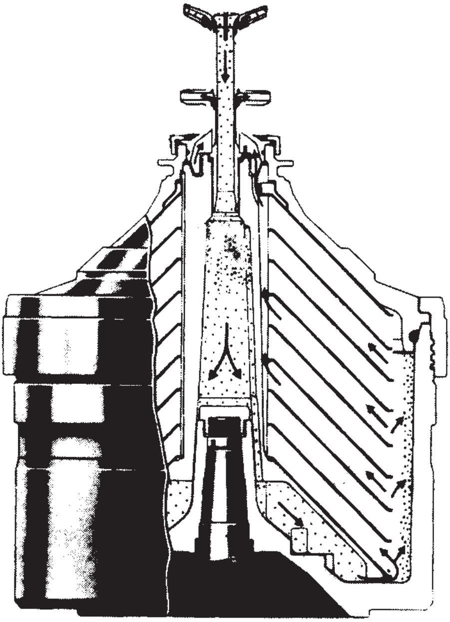


Figure 7.6 Disc-stack centrifuge operation

The number of discs depends primarily on the overall height of the bowl. To ensure good balancing, the ratio of the outside diameter of the bowl to the bowl height must not be much below unity. The number of discs also depends on the disc thickness, which is limited by the mechanical stability of the discs. The spacing of the discs depends on the concentration of the solid matter in the feed liquid, the solid particle size and consistency, and must be wide enough to prevent clogging.

Disc-stack centrifuges are particularly suitable for separating and clarifying liquids, where there is a small to moderate proportion of suspended solids present. Although there are many solids-retaining versions in use, most of these machines have some way in which the separated solids can be discharged, either continuously – in the nozzle bowl centrifuge – or semi-continuously – in the valved nozzle or opening bowl variants – which can be automatically controlled by the amount of solid separated, and so are effectively continuous. It should be noted that to the manufacturer of a disc-stack centrifuge the machine is commonly known as a separator, and frequently as a 'high-speed separator'.

Solids-retaining separators

The original type of disc-stack centrifugal separator is the solids-retaining machine, used on liquid–liquid or liquid–solids separation when the solids content in the feed is very low: up to a maximum of 1% by volume. Because of its mechanical simplicity this type of centrifuge can attain a very high G-force and is thus very efficient for separating two liquids with simultaneous removal of small quantities of solids, for polishing liquids or for recovering fine particles. Figure 7.7 shows a cut-away view of a disc-stack separator used for liquid–liquid separation (as also does that in Figure 7.6).

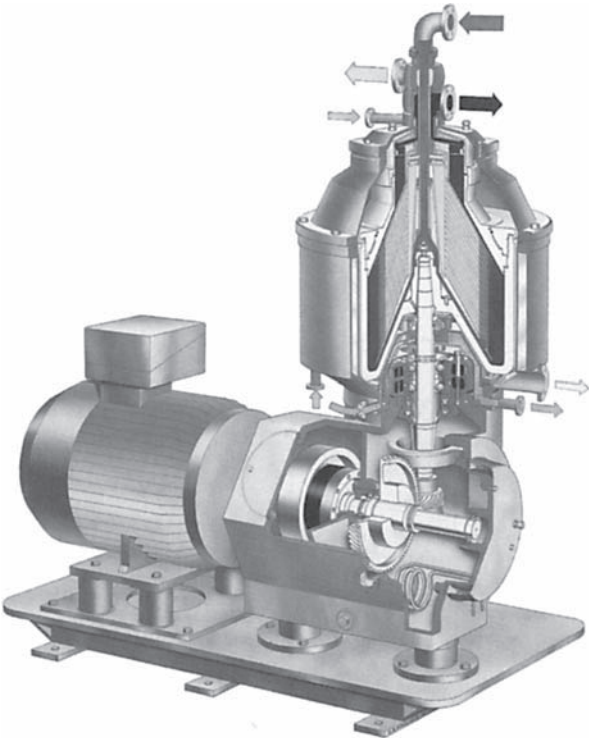


Figure 7.7 Liquid–liquid disc-stack centrifuge

Centrifuges designed as separators employ a disc stack, an array of thin cones mounted one above the other around the central axis of the bowl. Physical separation of the two liquid components (and the suspended solids) occurs within the disc stack, the light liquid phase accumulating near the bowl axis, and the heavy phase building up at the bowl wall. The dividing surface between the two regions is called the separating zone; this should be located along the line of the rising channels for the most efficient separation. The rising channels are a series of holes evenly spaced around each disc and arranged so that each vertical row of holes provides a vertical channel through the entire disc stack. The location of the separation zone is controlled by adjusting the back pressure of the discharged liquid phase or by using exchangeable ring dams at the liquid exits.

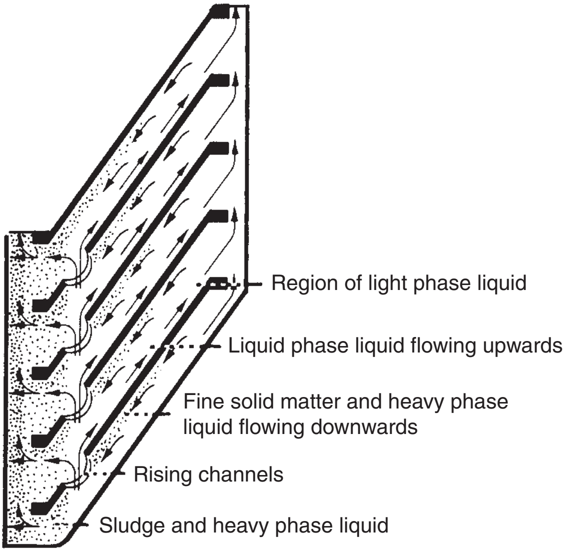


Figure 7.8 Operation of disc-stack centrifuge

These rising channels also provide the entrance for the liquid mixture into the spaces between the discs. As centrifugal force separates the two liquids, the solids move outwards to the sediment holding space adjacent to the bowl wall. A channel is shown in Figure 7.8, which illustrates the operation of the disc stack by means of a cross-section through half of the stack, the axis of rotation being to the right of the section.

An enclosed design of disc-stack centrifuge uses double pump discharge of the separated liquids, which keeps them under pressure. They are used primarily for mixtures where the heavy and light liquid components are approximately equal in volume. Double pump separators are particularly suited for the separation of volatile mixtures containing solids, where valuable products might evaporate. The double pump configuration also minimizes danger from either liquid phase. Pressurized liquid discharge has the additional advantage of reducing or eliminating pumping requirements downstream of the centrifuge.

Solids-ejecting separators

Solids-ejecting separators are normally used when the continuous clarification of a process liquid is desired, together with relatively continuous discharge of the separated solids phase. This type of centrifuge discharges the separated solids around the periphery of the bowl, either continuously through a series of small openings (just large enough to allow a thick slurry to pass, but not the liquid contents of the bowl), or intermittently through a set of openings whose discharge period and interval is dependent on the solids volume in the liquid to be separated. If the solids concentration is fairly constant, the interval is controlled by a timer or by means of a built-in hydraulic system.

Generally, the solids-ejecting separator is used when:

- the required clarity of the separated liquid is very high
- the solids are sub-micrometre particles
- the solid particles are sticky, hazardous or otherwise difficult to deal with
- the solids concentration in the feed is high, and
- the solids concentration in the feed varies and cannot easily be predicted.

The nozzle separator

The disc-stack centrifuge with continuous solids discharge is called a nozzle discharge machine. The special nozzles mounted in the periphery of the bowl allow for continuous operation with a liquid–liquid-solid feed, separating this mixture into two relatively clean liquid streams and a thick solids suspension. The concentration of this solids discharge can be controlled to meet process requirements.

A more refined version of the nozzle type of centrifuge has valved nozzles, in which each nozzle is individually closed by a valve, hydraulically opened when the solids level in the bowl reaches a pre-defined level.

There are several important considerations in evaluating whether or not the nozzle centrifuge is the most effective choice when confronted with a liquid–liquid–solid separation problem. Some of these considerations are:

- particle size: experience has shown that the ideal particle size range for nozzle centrifuges is between 0.1 μm and 30 μm in diameter
- density difference: the greater the difference in density between solid-liquid, and liquid–liquid elements to be separated, the more effective the centrifugal separation will be
- feed material characteristics: these are important to centrifugal separation efficiency (they include particle shape – sphere, plate, filament, etc., tendency to flocculate or disperse, hardness, corrosiveness of the liquid, degree of homogenization of the two liquids, foaminess, vapour pressure, etc.) – should there be any doubt, laboratory test work or pilot-plant experiments will indicate whether a given slurry sample is a viable prospect for effective centrifugal separation
- viscosity: the lower the viscosity the better the separation
- temperature: higher temperature slurries generally yield more effective separations as heat lowers viscosity and increases density differences.

It is important to note that the decision on whether or not to use a centrifuge in a given separation situation should be based on economics and degree of product yield.

The quantity of suspension concentrate that is discharged is not dependent on the density of the feed liquid, but is a linear function of the bowl speed, the number of nozzles and the radius on which the nozzle outlet lies. It also varies as the square of the nozzle diameter. The obtainable solids concentration is a function of the volume of concentrate discharged by the nozzles, the initial feed liquid concentration and the initial feed liquid volume. With a fixed rotational speed and fixed number of nozzles, and with a given feed liquid concentration, the discharge concentration can be adjusted by varying the nozzle diameter and an initial feed liquid volume.

Figure 7.9 shows a horizontal section through the bowl at the level where the solids enter the nozzle channel, from which it will be seen that the solids accumulate in segments between the nozzles. These segments must not be allowed to extend inwards into the disc stack, as this would have a deleterious effect on clarification efficiency. Solid matter accumulating in the segments is not discharged from the bowl, which cannot therefore empty itself completely when the feed is shut off (and therefore will need manual cleaning, although not necessarily until after a long run).

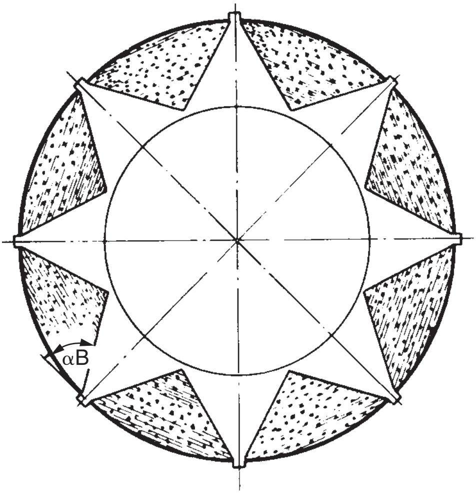


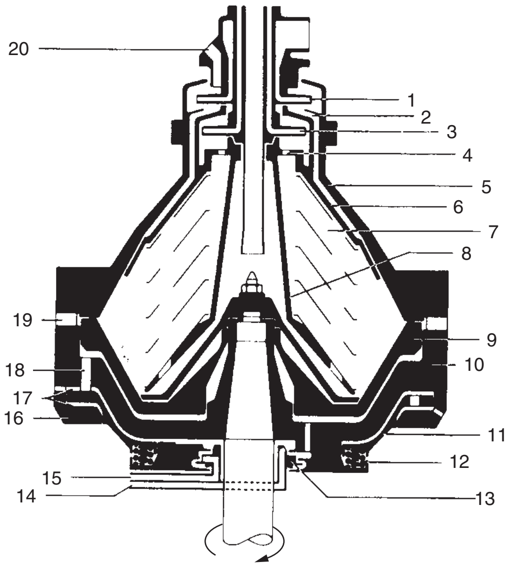
Figure 7.9 Solids accumulation in a nozzle bowl

A strainer or prefilter must be included in the feed lines of nozzle type centrifuges, to retain coarse impurities that are likely to clog the nozzles. The diameter of strainer holes should be about 50% smaller than the diameter of the nozzles.

Opening bowl centrifuge

A quite distinct form of the self-cleaning separator, the opening bowl design, has the bowl split into two parts at its widest point. Under automatic hydraulic control, initiated by solids level in this region of the bowl, the bowl components move apart or a closing sleeve is retracted (Figure 7.10). The separator bowl is equipped with a conical disc stack, with a wide top disc for the liquid seal and interchangeable gravity discs at the water outlet covering the normal range of specific gravities likely to be encountered. Dual paring disc pumps are provided for the pressurized discharge of both the clean oil and water phases, and a gear-type feed pump on the lower frame is driven from the worm wheel shaft.

To close the bowl in readiness for separation, dosing water from the separate operating water tank is fed into the compartment below the sliding bowl bottom.



1. Water paring disc.
2. Gravity disc.
3. Oil paring disc.
4. Level ring.
5. Bowl hood.
6. Top disc.
7. Disc stack.
8. Distributor.
9. Sliding bowl bottom.
10. Bowl body.
11. Operating slide.
12. Spring.
13. Operating water paring disc.
14. Opening water supply.
15. Closing and make-up water supply.
16. Dosing ring.
17. Dosing ring chamber.
18. Drain valve.
19. Sludge port.
20. Liquid seal and flushing water supply.

Figure 7.10 Opening bowl disc-stack centrifuge

This water supply remains open as long as the machine is in operation, maintaining the static head.

To build up the liquid seal in the bowl, a valve in the water outlet pipe is closed and water from the operating water tank is fed direct to the sludge space of the bowl, through the water paring disc chamber, and the space between the bowl hood and the top disc. When the water has reached a radial level inside the outer edge of the top disc, the liquid seal is established and the feed slurry can be introduced to the bowl. With the sludge ports closed, the feed flows continuously into the bowl, and clean oil and separated water are continuously drawn off by the paring disc pumps. Sludge accumulates at the periphery in the angle between the bowl hood and the sliding bowl bottom. This sliding component is then lowered to give controlled discharges, either manually, or by an automatic timer at regular intervals chosen according to the sludge content of the water, or hydraulically operated by the level of solids in the sludge compartment.

In the chemical and process industries, and increasingly in biochemical processing, the completely self-cleaning opening bowl centrifuge has been an established piece of equipment for over 40 years. It operates with developed G-forces in the region of 6000 to 9000, giving a separation efficiency equivalent to about 50,000 m^2 of static settling area, in a machine occupying a floor space of perhaps 2 m^2. Characteristic of its operation is the intermittent removal of separated solid phase from the centrifuge bowl, while the machine is running – although in reality the opening and actions are extremely fast, with the bowl remaining open for a mere 20–30 milliseconds.

Hermetic centrifuges

Totally enclosed or hermetic centrifuges with disc-stack bowls are used for clarifying feed liquids whose pressure must not be allowed to fall. The feed and discharge connections are attached to the rotating bowl by airtight mechanical seals that move in accordance with the slightly eccentric rotation of the bowl. Either collars made of flexible material or sliding ring seals made of carbon are used.

Hermetic centrifuges may be used in pressure systems up to 8 bar in situations where:

- the feed liquid cannot withstand the impact on entry into the rotating bowl, i.e. when the particles to be removed are liable to be destroyed at the inlet, such as protein – since the bowls of hermetic centrifuges are filled right to the centre, the feed liquid is gently brought up to the bowl speed by means of the liquid friction immediately on entry, and
- the feed liquid is easily oxidized, emits gas or evaporates.

In breweries, for example, hermetic centrifuges can be used for pre-clarification of beer ready for packing, with no carbon dioxide losses and no destruction of protein; for the clarification of the cold wort, with a good clarification efficiency because protein particles are not destroyed. In dairies, hermetic centrifuges are used because milk is sensitive to both oxidation and shear.

The scroll discharge (decanter) centrifuge

The decanter, a cylindrical centrifuge designed for liquid clarification and solids recovery, meets widely varying process requirements in food and chemical plants, oil refineries, pulp and paper mills, minerals processing plants and in municipal and industrial waste disposal. Decanter centrifuges are increasingly being used for the separation of solids from suspensions in liquids, an essential condition for the decanter centrifuge to function being that the solids density must be greater than that of the liquid, although the difference does not have to be very great. Decanters are used for the separation of coarse solids such as PVC granules, as well as for the separation of fine solids such as minerals or activated sewage sludge. In addition, solids can be dewatered as well as separated in decanters.

Solids are continuously separated from the feed suspension by the action of the centrifugal force generated within the unit by virtue of its high speed rotation. The feed slurry is introduced through a stationary feed tube situated on the axis of the unit, and is accelerated up to the machine speed by an impeller in the feed zone (Figure 7.11). It is then distributed into an annular liquid pool, or pond. Here the solids are moved by centrifugal force to the inner wall of the rotating bowl, where they would stay, were it not for the scrolling action of a screw conveyor. This conveyor rotates continuously on the same axis as the bowl but at a slightly different speed. In this way the accumulated solids are carried towards the solids discharge (conical) end of the bowl.

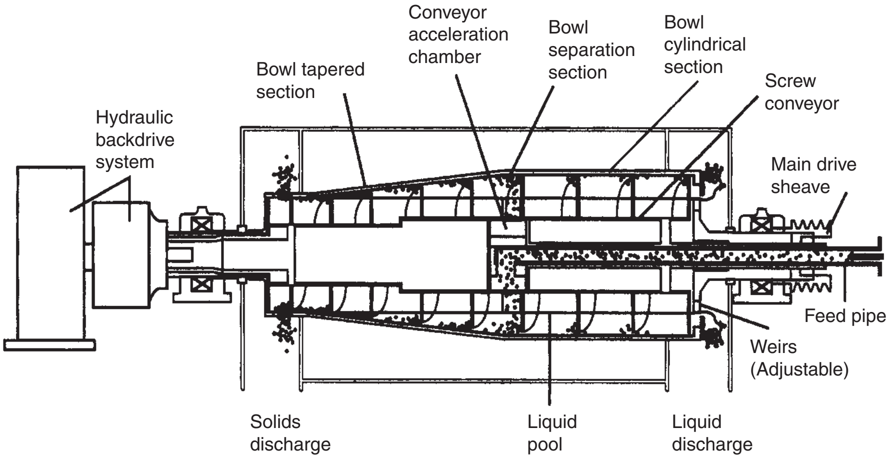


Figure 7.11 Decanter centrifuge

The liquid layer at the rotating bowl wall is maintained at the desired pond depth by the location of overflow weirs. These are adjustable ports located at the closed end of the bowl. The solids are continuously moved by scroll action to and then up the conical end of the rotating bowl, out of the pond, to drain as they move up the beach. Finally, the solids are ejected from the open end of the bowl, thrown radially into a stationary collecting chute in the machine's casing, from which they drop into a container.

Decanter centrifuges can be classified into three types:

- solid bowl centrifuge with counter-current flow
- solid bowl centrifuge with co-current flow, and
- screen bowl design.

Of these, the counter-current design is by far the most common.

Conventional decanter centrifuge bowls consist of a cylindrical and a conical part. The solids are separated in the cylindrical part, while the conical section is mainly used to drain and dewater the solids. The cone angles are normally between 5° and 12°, with the cone forming up to 50% of the entire length of the centrifuge (and in older designs the whole length).

In the counter-current flow version, the feed suspension enters the bowl roughly level with the junction of conical and cylindrical sections. A large proportion of the fed solids drops out of suspension very quickly, and is carried off up the beach by the scroll. The liquid then flows along the cylindrical section, to its far end, with residual settling occurring during this time, and with these solids in turn scrolled along to the beach.

In the co-current version, feed is at the liquid discharge end, giving the whole bowl length for sedimentation. Care is necessary in design to ensure that solids do not escape into the clean liquid discharge, and this version requires that the whole solid volume is conveyed the whole length of the bowl, with consequently increased torque on the conveyor.

There are a number of different discharge methods available that have been specifically developed to overcome certain problems. These include radial discs or plates, deep pond methods, skimmer discs and the use of air pressure. Discharge by nozzles located in the cylindrical part of the centrifuge is another method that has been tried.

The *vertical decanter*, hanging from drive and bearings at the liquid discharge end of the bowl, was developed to meet the requirements of the chemical industry to overcome a temperature and pressure problems – it is much easier to pressurize the vertical design.

The disc-stack centrifuge is easily able to separate two liquids (for which it was originally designed), and somewhat less easily a separate solid phase. The decanter was developed as a way to clarify a single liquid stream effectively, with quite high feed concentrations. However, a decanter has now been developed that can handle two immiscible liquids. The *three-phase decanter* has the same kind of solid discharge (except that the upper liquid layer may be kept from the beach), but has two sets of liquid layer discharges at the other end.

The screen-bowl centrifuge (Figure 7.12) differs from the standard decanter centrifuge in that the conventional cylindrical/conical bowl is followed, beyond the conical section, by another cylindrical section in the form of a screen. The screen is usually made from wedge-wire bars, welded so that their slots run parallel with centrifuge axis. This arrangement provides for combined sedimentation and filtration, increasing the degree of dewatering of the discharged solids, which now overflow from the bowl at the edge of the screen. Screen-bowl centrifuges are used in the processing of coal flotation concentrates, potassium and rock salt solutions, ammonium sulphate, paraxylene and milk sugar. The plastics industry also successfully applies screen bowl centrifuges for extracting moisture from PVC, polyethylene, DMT and similar products.

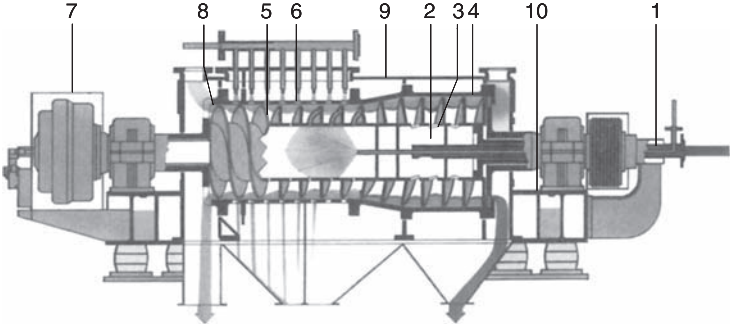


Figure 7.12 Screen-bowl decanter. (1) Feed pipe, (2) feed compartment, (3) feed compartment outlets, (4) bowl, (5) internal screw, (6) screen section, (7) gearbox, (8) discharge ports, (9) centrifuge case, (10) base frame.

7D. CYCLONES AND HYDROCYCLONES

Cyclones, which separate solid particles from gases, and hydrocyclones, which separate the particles from a liquid suspension or which separate one liquid from another, are dynamic separators working on the principle of inertial forces generated by the velocity of the incoming fluid stream. As with centrifuges, the rotational action of the fluid creates a centrifugal force, so that the settling rate given by Stokes' law for normal gravity settling is now multiplied by the extra rotational force, $r\omega^2$.

Cyclones are basically aerodynamic or hydrodynamic separators, in which the fluid being handled is caused to develop a vortex flow, as a result of which the more dense particles are thrown out of the main fluid stream. Since cyclones work according to the mass of the particles involved, they may also be applicable to the separation of light and dense solids in suspension from one another, or of mixtures of liquids. The same principle is also utilized in pipeline air filters for separating out water and oil droplets, and heavier solids, before the contaminated air actually reaches a filter.

Cyclones may be dry or wet in operation, with dry cyclones providing solid-gas or liquid droplet-gas separation as in air or gas cleaners. Wet cyclones provide solid-liquid or liquid–liquid separation, and are specifically described as hydrocyclones.

Hydrocyclones operate under pressurized conditions and, where sufficient pressure is not already available in the feed, pumping is required. Capital and operating costs are generally low and hydrocyclones are particularly suitable for classification as well as basic separation duties.

In the hydrocyclone, the material to be processed is separated into a solids concentrate and a thinned suspension of fines. The concentration is achieved by a combination of centrifugal and gravitational action. The feed suspension is introduced tangentially with a high velocity at the top of the shell of the hydrocyclone (Figure 7.13), whence it descends in a helical path on the inside of the shell. The circular motion provides a sizable centrifugal acceleration, causing the larger particles to be thrown out of suspension towards the shell wall, ultimately to be discharged from the bottom of the conical base of the shell, together with some of the liquid, as determined by the angle of the cone. The residual liquid and the unseparated fines ascend in the axial direction and closer to the axis, and leave the system through a vortex finder in the centre of the top of the shell.

Hydrocyclones have no moving parts and can be fabricated from materials that resist both abrasion and corrosion. They require a relatively small operating pressure, between 1 and 2 bar, usually provided by a centrifugal pump. Hydrocyclones are used for functions such as classification, clarification, concentration, counter-current washing, de-gritting, de-sliming and solids recovery. They are used singly or in batteries as a separate processing station, or in combination with other equipment.

Individual cyclones can handle exceptionally large flow volumes. For the most part assemblies of hydrocyclones are less costly than other types of separator. Also,

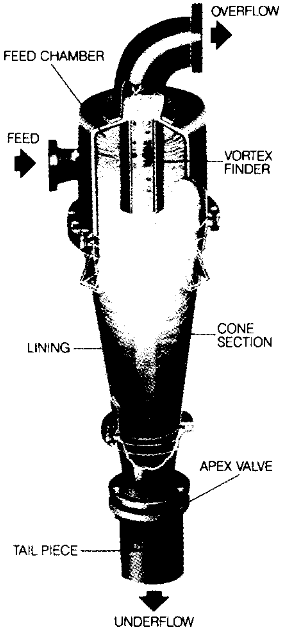


Figure 7.13 Hydrocyclone internals

used ahead of expensive equipment processing gritty feed streams, they can save money by reducing system abrasion.

Hydrocyclones are not normally used for removing coarse solids that are greater than 0.5 mm in size, although there are some exceptions. To perform efficiently, a cyclone needs materials with a sufficient differential in specific gravity between the fractions being separated. The cyclone performs best with solids fractions that have large density differentials and with less viscous liquids, but the question of how dense or viscous is a matter for testing. A cyclone cannot totally remove all liquid from concentrated solids suspensions – some liquid is necessary to achieve discharge of the solids.

Cyclones are also used as de-aeration devices with centrifuges. Because of air movement in the casing of a centrifuge, the centrate often leaves the centrifuge mixed with a large volume of air. A liquid-gas cyclone directly attached to the centrate outlet provides effective de-aeration.

Hydrocyclones fitted with replaceable elastomeric wear liners are widely used in a number of applications where the solid material in suspension is abrasive, including mineral processing, flue gas desulphurization and coal processing. Some examples of the wide range of use are shown in Table 7.1.

7E. COALESCERS

Separating liquid–liquid dispersions can be difficult and costly, depending on the physical properties of the two liquid phases. Liquid contamination in the oil, gas

Table 7.1 Hydrocyclone applications

1	Sizing of particles	a	Removal of sized crystals from crystallizing systems, the overflow returning for further concentration
		b	Removal of coarse particles from thickener feeds with substantial reduction in consumption of flocculants
		c	Preparation of filter feeds
		d	Preparation of finely sized abrasives
		e	Preparation of ceramic clays
		f	Cleaning of filter bed sand
2	De-gritting of water or suspensions	a	Desanding of water supplies
		b	Removal of grit from paper pulp
		c	De-gritting of clays
		d	De-gritting of milk or lime
		e	Removal of grit and dirt from fruit juices
		f	Removal of grit and dirt from wool scour liquor
		g	De-gritting of effluents before discharge to settling ponds, to eliminate silting with great reduction in wear on pumps and pipelines
3	De-sliming	a	Removal of ultra-fine particles from granulated materials
		b	De-sliming ahead of leaching processes
		c	Removal of clay from building sands
		d	Preparation of mine backfill
4	Closed circuit grinding		This is the most important application of hydrocyclones. They are far cheaper than gravity settlement-type classifiers, occupy much less space and give more accurate separations.
			The high separating forces in a cyclone often enable separations to be made that are impossible in any other type of classifier or filter
5	Preparation of solutions or suspensions		By feeding controlled quantities of water and solids to a pump sump and pumping through a cyclone, solutions and suspensions can quickly be prepared without a mixer.
			This system works well in conjunction with a density controller supplying a signal to operate the adjustable apex value in the cyclone
6	Separation by specific gravity	a	Removal of organic matter from sugar beet effluent
		b	Removal of peat from sand
		c	Separation of shells from nut kernels
		d	Separation of light and heavy minerals, using a heavy suspension as the ‘medium’

and chemical industries, for example, can cause final products to be off specification, or cause de-activation of downstream catalysts, corrosion of downstream storage facilities, and increase the costs of wastewater treatment.

The specific gravity, viscosity and interfacial tension of the two liquid phases are important parameters in determining how easily two liquids can be separated. Generally, conventional coalescers begin to lose efficiency when the interfacial tension gets below 20 dyne/cm. Efficient separation is a function of the compatibility of the liquids with the coalescer medium. A good coalescer medium is not necessarily compatible with the liquids, and a compatible medium is not necessarily a good coalescer.

In a basic form, coalescers can be described as a special type of separator designed to collect highly dispersed droplets, present in a carrier fluid, and form or coalesce these droplets into large drops that will rapidly separate out of the carrier fluid. Specifically, they are used to separate water from oils, and most commonly from fuel oils.

The principle by which this is done is to pass the water-contaminated oil through a dense inorganic fibre bed or filter mat. Water droplets are intercepted by, and impinge on, the fibres. The oil on the fibres is thinned by displacement and the effect of viscous drag, until ultimately the oil film ruptures and allows the water droplets to attach themselves completely to the fibre, with the oil film dispersed and passed on through the mat. Other water droplets are now collected by the fibres in a similar matter, and these will join with others, forming streams along the fibres.

The droplets continue to grow in size until drag and gravity forces break them away from the fibre, and they drop off the filter mat into a sump. In practice, a final stripping stage is usually desirable, such as a fine mesh screen located downstream of the coalescer to collect smaller water droplets, which may spin free and be carried along with the oil stream, rather than settle under gravity.

A cutaway drawing of a filter/coalescer is shown in Figure 7.14, in which contaminated oil fountains out through holes in the top section of a centre column, mounted through the division plate. Oil then flows from the inside to the outside of the two-stage cartridge. Particles are arrested by the synthetic prefilter element, and water is coalesced from the oil within the inorganic coalescer element. Filtered oil then passes through a PTFE-coated metal mesh, which ensures the absence of residual free water carryover. Clean dry oil finally flows up to an outlet at the top of the unit, whereas the coalesced and stripped water forms droplets large enough to fall by gravity through apertures in the division plate, into the sump. The cartridge is an integral unit consisting of prefilter and coalescer elements encased in perforated cylinders for rigidity.

Prefilter elements are made from a specially developed synthetic fibre medium, which is pleated, with the folds separated by means of spacers. The structure provides a good dirt-holding capacity, eliminates element distortion, and ensures that the complete filter area is utilized to maintain maximum flow. In addition to removing particulates down to 5 μm, the prefilter protects the coalescer element from excessive quantities of particulate contaminant. This is especially important in applications treating diesel fuel, where pipe scale, rust, waxes and asphaltines might otherwise block the fine pores of the coalescer element.

The coalescer element consists of a cylinder of fine inorganic fibres, pressed to a predetermined density and depth, sufficient to ensure maximum water coalescing action. The element is also designed to maintain a flow of relatively low velocity through its depth to ensure efficient water removal. Flow rates that can be achieved, through a cartridge measuring 435 mm long by 216 mm diameter, are approximately 1400 l/h for diesel fuel and 500 l/h for lubricating oil.

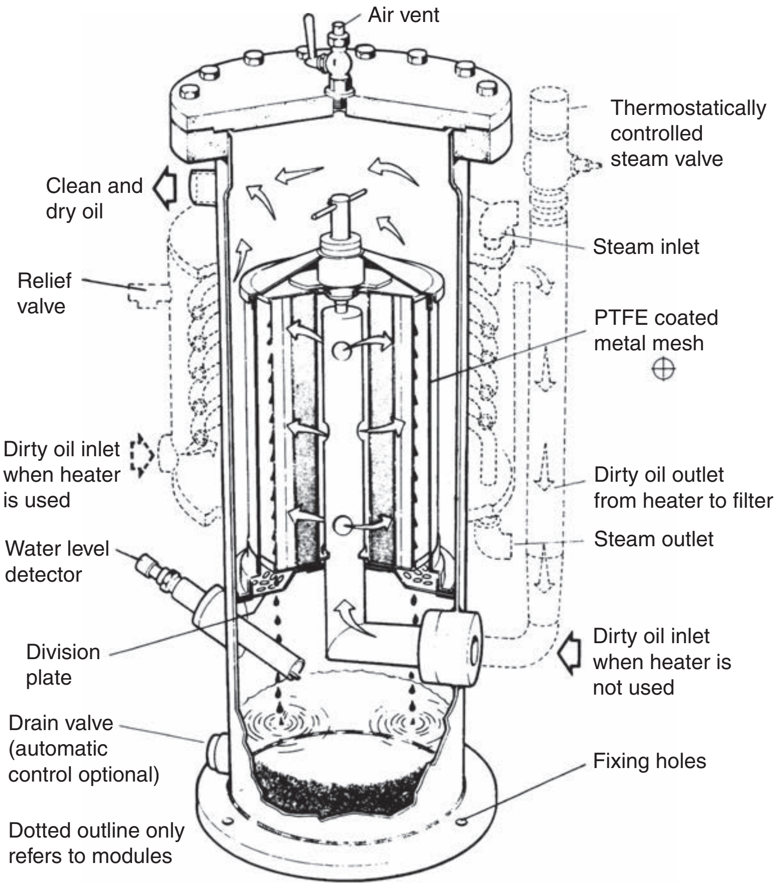


Figure 7.14 Filter/coalescer operation

Typical industrial applications for coalescers include the:

- removal of carried-over caustic from refinery fuels, downstream of caustic treating processes
- separation of various oils from water
- removal of water and caustic from on-line analyser systems
- separation of water from hydrogen peroxide working solutions
- separation of hydrogen peroxide working solutions from hydrogen peroxide
- removal of carried-over amine from hydrocarbon, downstream of a liquid–liquid amine contactor, and
- removal of oil from ammonia.

To extend the life of a coalescer, and to reduce particulate concentration, so as to meet fluid specifications, solid contaminants should always be removed with a prefilter.

Removal of solids also decreases the stability of the liquid–liquid emulsion, making liquid–liquid separation easier.

Generally, with coalescers, the overall cost of contaminant removal can be low, even when compared with other less efficient methods, like salt driers, electrostatic separators and sand filters.

Coalescers can also be used to remove water from lubricating oils, hydraulic oils, etc., provided that these contain no detergent additive. Detergents reduced interfacial tension and inhibit formation of large droplets on the coalescer.

7F. WET AND DRY SCRUBBERS

Generally speaking, a scrubber is a device used to clean or purify an air or gas stream, free from suspended solid particles or liquid droplets, or from gaseous impurities. It can consist of a packed bed of solid granules, which acts as a deep-bed filter, or of a spray tower with the contaminated gas passing up the tower against the flow of a liquid spray (as in Figure 7.15), or of a packed bed of granules, with a liquid trickling over the granules. They may work by physical processes (filtration, absorption) or by chemical reaction, and if a liquid is involved, they are called wet scrubbers, otherwise they are dry scrubbers.

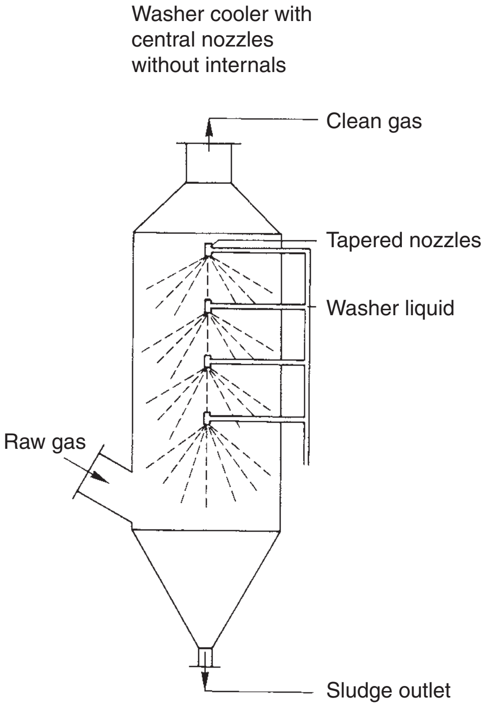


Figure 7.15 Spray tower wet scrubber

A successful scrubbing process is a question of choosing the various items of equipment and/or scrubbing liquid capable of collecting pollutants or combining with them to achieve maximum separation efficiency. Scrubbers use the principle of absorption to remove mists, vapours and gases such as hydrogen chloride, hydrogen fluoride, sulphur oxides, ammonia or chlorine into a liquid solution. Scrubbers also range among the simplest dust arresters and can be used in a multitude of other applications, including gas cooling, noxious gas removal, and as conditioners upstream of electrostatic precipitators.

Particle size is the main parameter limiting the efficiency of dust collection. The relative velocity of gas and liquid, or impact velocity, is also a key factor in scrubber efficiency. For equal efficiencies, gas velocity is inversely proportional to the square of the diameter of the particles. This means a very high energy requirement as dust particle size falls, especially below 1 μm, particularly as the turbulence due to high energy encourages agglomeration through the Brownian effect and van der Waals electrostatic forces – these factors are decisive with particles below 0.2 μm.

The overall efficiency of a scrubber is proportional to the chances that all the particles flowing through it collide with an obstacle on their way. Theoretically, wet scrubber efficiencies are inversely proportional to liquid droplet diameter and directly proportional to droplet quantity (spraying ratio). In practice, droplet agglomeration due to high turbulence limits these influences considerably and it is unrealistic to attempt to improve the performance of a scrubber by seeking finer spraying and a higher spraying ratio.

Vapour condensation is an important factor in improving scrubber efficiency. Condensation on smaller particles acting as nuclei results in their becoming bigger and thus encourages agglomeration. Condensation on cold droplets pulls vapour towards them and so draws particles together. Especially when working with fine particles, it is necessary to precool and saturate the gases.

Wet scrubbers

Wet scrubbers are particularly intended to wash fume- or dust-laden gases with a spray or sheet of water to remove such contaminants as are present, leaving only clean air or gas to be exhausted from the system. They are capable of handling many fume and dust control problems arising from industrial processes, and are particularly applicable to hot gas processes, where it is possible to quench the gas stream by direct introduction of water as close to the process as possible. Quenching in this manner makes the dusty gas stream very much easier to handle.

Scrubbers may be open or fully enclosed. An example of the former type is the venturi scrubber used on a process vessel or storage tank, which needs to breathe, but as a consequence can release objectionable fumes. The action of water sprayed into a venturi section creates suction, drawing the fumes into the scrubber, where they are removed and carried down by the scrubbing water, leaving only cleaned gas together with entrained water to be exhausted.

The efficiency of such an arrangement is largely dependent on the venturi design and the forced water injection system, yielding maximum scrubbing energy (i.e. maximum pressure drop). With venturi-type scrubbers, high water feed rates are necessary, but savings can be realized by recirculating the water through a suitable water cleaning system.

Entrained moisture in the exhaust gases will be in droplet form or as a mist, which may or may not be acceptable. In some processes, for example, the scrubbing liquid may not be water but an aggressive fluid, such as an acid, when it is obviously necessary to eliminate this from the final exhaust by some form of demister, such as mist eliminator pads or blades. The latter are more efficient, have a lower pressure across the eliminator, and are better able to handle any dust remaining without clogging. Alternative dedusting units include elementary centrifuges, cyclones etc.

Other types of wet scrubbers in common use include spray towers, vertical and horizontal packed towers, jet ejectors, extended surface scrubbers, fan spray scrubbers and various individual designs, some of which may be described as cleaners.

Semi-dry scrubbers

Semi-dry scrubbers involve a chemical reaction with a wet slurry, and a dry scrubbing of the gases with dry collection of co-products. Typically the process is used to treat acid gases in a spray dryer, coupled with a pulse-jet fabric filter. In the scheme shown in Figure 7.16, with a vertical downflow spray dryer, an alkaline slurry is injected to neutralize the acids present in the flue gas. The gas temperature is controlled by the flow rate of the dilution water.

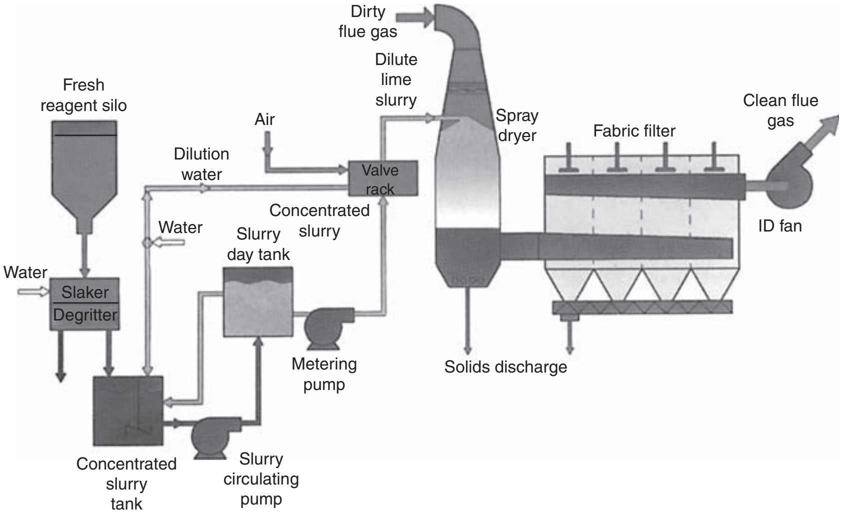


Figure 7.16 Acid gas cleaning

The sensible heat of the flue gas evaporates the water present in the slurry, leaving fine, dry particles of salt, fly-ash and excess alkali to be collected in the fabric filter. As the gas passes through the cake on the filter bags, a further reduction of the acid gas occurs as it reacts with the excess reagent in the filter cake. The purified exhaust gases are then vented through a chimney equipped with a continuous monitoring system. The collected fly-ash, salts and a minimal quantity of excess free agent are then transported from the fabric filter hoppers by mechanical or pneumatic conveying systems to a solids storage silo. A particular advantage of this process is that it allows control of high acid gas concentrations in large gas volumes.

Dry scrubbers

A simple dry scrubber employs a packed bed of inert or reactive material, to remove contaminants, either by deep-bed filtration or chemical reaction.

An all-dry scrubber uses powdered reagent sprayed into the exhaust gas stream, followed by a fabric filter, to collect the solids and provide a final site for the reaction to be completed. The solids from the filters can be recycled for further gas cleaning.

Hydrostatic precipitator

A hydrostatic precipitator can be described as a centrifugal scrubber or a wet centrifuge. It is essentially a wet dust collector where dust is washed out of the air or gas by the combined action of the intermixing of water and dust-laden gas and of centrifugal force.

The machine relies upon a forced flow of contaminated air to pick up a quantity of water that then washes the air in an inertial separator section. Air flowing through a stationary impeller at high velocity picks up the water in a turbulent sheet. The centrifugal force exerted by rapid changes in flow direction causes the dust particles to penetrate the water film and become permanently trapped. The water is continually re-used and since the water curtain is produced by the air flow, no pumps or nozzles are required.

Regardless of the volume of air being handled, the water level is maintained at the same elevation on the clean air side. As air flow reduces, pressure lost through the precipitator's impeller decreases, causing make-up water to raise the water level on the dirty air side. This higher operating level throttles the air passage in the impeller, and increases the air velocity through the narrowed opening. An almost constant approach velocity causes the same volume of water to be impelled through the passages by the air stream, so that the scrubbing action and collection efficiency at reduced air flow ratings are maintained.

7G. MIST ELIMINATORS

Most chemical or petrochemical process gas streams contain various liquid droplets. These are caused by condensation, such as after cooling processes, or generated by liquid injection in absorption or gas scrubbing processes, or by carry-over in evaporator processes, or generated in a chemical reaction process in the gas phase. To eliminate the predominantly very small droplets inherent in these processes is the task of the mist eliminator.

These droplets: tiny particles of liquid or solutions of dissolved solids, suspended in a stream of gas, can cause problems such as corrosion of equipment, contamination of products, fouling of heat exchangers and catalysts, and damage to instruments. When released into the atmosphere, these droplets can cause violations of air pollution standards or of opacity regulations.

The mechanical performance of a mist eliminator is measured by two curves: the collection efficiency versus particle size, and the pressure drop versus the vapour load. To operate at high efficiency, a mist eliminator should have a fibre or mesh pad with a high surface area to volume ratio.

An often-used rule of thumb in mist pad selection is droplet size prediction. First, entrainment arising from mechanical processes, such as boiling, two-phase processes, seal leakage, surface condensation, etc., typically produces droplets larger than 20 μm. Second, entrainment arising from chemical processes, such as reaction, endogenous condensation, etc., typically produces droplets in the sub-micrometre range. Chemically produced droplets should therefore be encouraged to coalesce before collection using a mist pad. Collisions between droplets cause coalescence, and a process of droplet size enlargement.

The key elements of performance of a fibre or mesh mist pad are efficiency, re-entrainment, pressure drop and corrosion resistance. When comparing the efficiencies of mist eliminators, it is appropriate to consider efficiency on the basis of the percentage of particles collected, classified by particle size rather than by weight. This distinction is important because many problems, such as opacity, are caused primarily by the smaller particles. Because a 0.5 μm particle has only one thousandth of the weight of a 5 μm particle, some mist eliminators can easily achieve 99% or higher efficiencies on a total weight basis, without collecting any of the smaller particles at all.

A typical fibre bed mist eliminator, as shown in Figure 7.17, consists of any one of a variety of fibres (glass, polyester, polypropylene or Teflon) packed in a supporting cage constructed from metal or fibreglass reinforced plastic, or polypropylene, material. Gases containing sub-micrometre liquid droplets are directed horizontally through a bed of these fibres. Droplets collect on individual fibres of the bed and then coalesce to form liquid films, which are moved through the bed by the gas flow. The collected liquid drains off the downstream face of the bed by gravity.

The use of mist eliminators to remove liquid droplets from industrial gases falls broadly into two categories: process gas cleaning (as a necessary requirement of the process involved), and exhaust gas cleaning (for environmental considerations). Typical industrial applications for the fibre bed mist eliminator include the removal of acid mist from sulphuric acid plant absorbing towers, the removal of soluble inorganic salts during fertilizer manufacture, and the removal of light organic oils from asphalt or plasticizer operations.

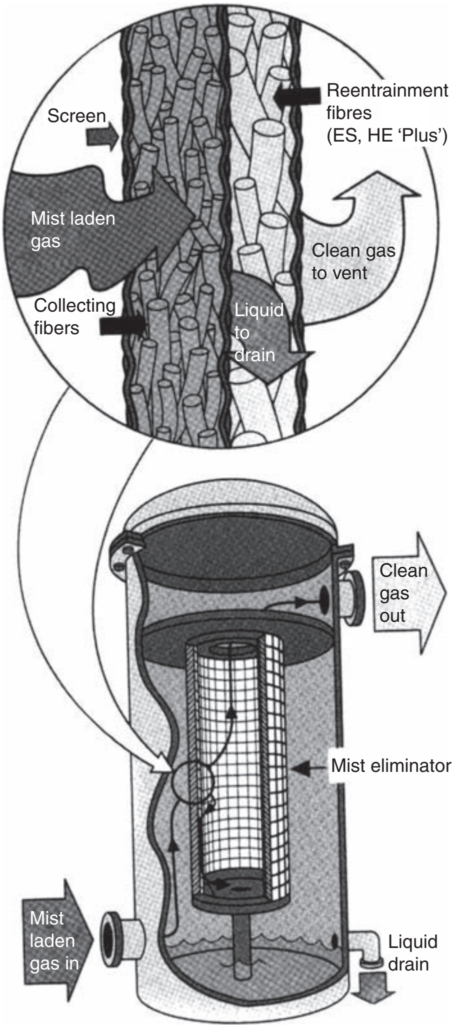


Figure 7.17 Fibre bed mist eliminator

Among the types of eliminator that are used are:

- filter packs, using fibrous or wire mesh elements
- candle filters
- cyclones
- electrostatic precipitators, and
- impingement filters.

The characteristics of these individual forms of mist eliminator are summarized in Table 7.2.

Table 7.2 Types of mist eliminators for industrial gases

Type	Operating mechanism	Assembly	Function	Remarks
Settling tank knockout drum	Gravity	Tank (upright or horizontal)	Slowing down of the gas flow so much that the settling velocity is higher than the gas velocity.	Simple, inexpensive apparatus for very gross drops, poor efficiency, rare use.
Fibre filter filtering candle	Mechanical filter	Case with compact packing of fibres on different single or individual filtering candles	Single drops are brought in touch with the fibres, flow together, increase and fall down due to gravity. The filtering candle prevents passing of droplets while gas flows through.	Voluminous apparatus with very low face velocity and low liquid loading preferably for very small drops; danger of clogging and build-up.
Electrostatic precipitator	Electrostatic forces	Case with electrodes	The drops are electro-charged and attracted to the collecting electrodes.	Complicated, expensive apparatus for extremely fine drops, very high efficiency, rare use.
Cyclone	Mass moment of inertia	Tank with installation which forces gas flow to rotate	Based on rotation separation because of varying density, the drops are eliminated along the tank walls.	Simple and voluminous apparatus for middle-sized drops, good efficiency, frequent use.
Wire mesh	Mass moment of inertia	Tank with pack of several layers of wire mesh of undulating wires; compact wire mesh with high porosity	The drops are brought in touch with the wire surface, flow together, coalesce and fall down due to gravity.	Voluminous apparatus with low face velocities for low liquid loading and very fine drops, danger of clogging and build-up.
Impingement eliminator	Mass moment of inertia	Tank with a set of profile plates of different types	Gas flow is split up into many single flows and repeatedly deflected. Due to inertia the drops cannot follow the flow of the gas and thus are eliminated on the impingement surfaces.	Small compact construction because of high face velocity, very high efficiency even for very fine drops, low pressure drop on well-formed profiles, increasing use.

Impingement filters are based on inertial effects with the gas flow being repeatedly deflected. Three configurations are employed: horizontal for vertical gas flow, vertical for horizontal gas flow, and inclined with gas flow at the same angle to the horizontal. Typically, an impingement eliminator is composed of corrugated profile plates assembled with phase separation chambers, mounted on a frame with a collection sump below them (as illustrated in Figure 7.18 for horizontal gas flow). The profiled plates split the gas flow into separate streams. The corrugations change the gas flow direction, but the inertia of the droplets causes them to go straight ahead and collide with the plates. The film that is produced is pushed towards the phase separating chambers, where gravity pulls the film of moisture down into the sump. The construction of the phase separating chambers aids the flow and reduces waste and eddying. By this means, loss of pressure is avoided at high velocities and less energy is expended.

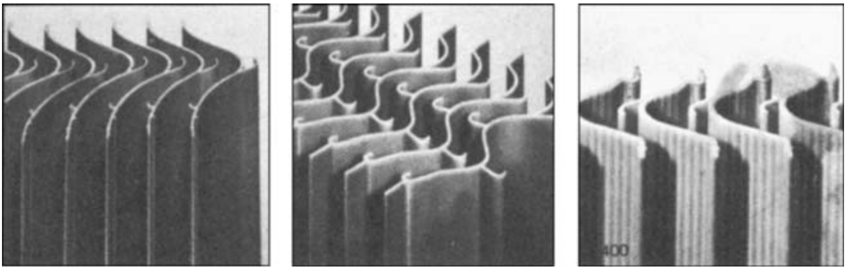


Figure 7.18 Mist eliminator profiles

Efficiency of capture can be improved by increasing the number of separating chambers incorporated, that is by providing two-phase, three-phase or four-phase separation. However, the optimum geometry depends on the type of eliminator (longitudinal, vertical or inclined) as affecting the collection and discharge of the liquid droplets.

Theoretically, efficiencies of up to 100% are possible, but practical efficiencies realized are lower, being restricted to a design limiting drop size. For a particular design of mist eliminator, the limiting drop size is a complex function of the face velocity.

7H. ELECTROSTATIC PRECIPITATORS

Electrostatic precipitation is an extremely effective method for removing dust, smoke and other small particles from air or exhaust gases over a particle size range from about 10 μm down to 0.01 μm or even 0.001 μm. The principle of the electrostatic precipitator involves passing the dusty air through an ionizer screen where electrons colliding with the air molecules generate positive ions, which then adhere to the dust particles present giving them a positive charge. (Positive ionization is preferred, since it eliminates over-production of ozone in air purification systems.) The charged dust particles then enter a region filled with closely spaced, parallel metal plates alternatively charged with positive and negative voltages of the order of 6000 V. The positive plates repel the positively charged particles, which are attracted by and retained on the negative plates by electrostatic forces. Once the particles settle on the plates, the electrostatic forces are supplemented by intermolecular forces, causing the dust to agglomerate.

Further treatment of the collected solids then depends on the system and application. Some plate regions are designed with relatively large spacing to allow a large thickness of solids to accumulate, before they need cleaning by rapping or vibrating with gravity release or by washing. This is usually the preferred method for continuous straight-through air cleaning. In other designs the agglomerate may be allowed to build up until the layer breaks down or flakes off, to be carried downstream by the air flow and collected in a baghouse or similar dust-holding device. This type of dry dust removal can be initiated at any stage by a separate purge air flow, and the filter bags are then changed as necessary.

Other alternatives include the use of a prefilter to remove larger particles before the ionizer section, and the incorporation of an adsorber element, such as activated charcoal, downstream of the plates to remove odours. An illustration of this straightforward type of electrostatic precipitator is shown in Figure 7.19, employing a coarse prefilter. Dust and other solid contaminants remain on the plates until removed by washing, if required. Liquid contaminants collected on the plates will drain off to the bottom. Power requirements are a normal mains voltage supply, the required DC potentials of 13,000 V for the ionizer and 6500 V for the plates being generated by a power unit based on a high voltage transformer and a doubler circuit.

Because an electrostatic precipitator has no effect on gaseous impurities, it is usual for such a separator to be fitted with an odour removing activated carbon filter

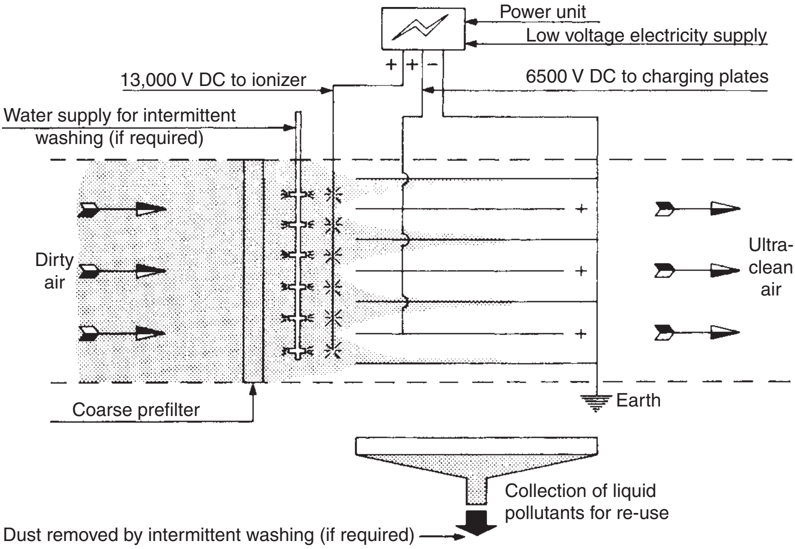


Figure 7.19 Simple electrostatic precipitator

at the downstream end of the system, after any particulate collection filter (so that the carbon filter does not become clogged).

Wet precipitators are used where aerosol mixtures must be separated with a high efficiency from waste air, circulating air or process gas. These will have drip trays below the collection plates. A typical plant-scale horizontal wet electrostatic precipitator is shown in Figure 7.20, for which applications include tar separation from coke-oven gas, separation of recondensed lubricant and resin vapours, paints mist and oil mist.

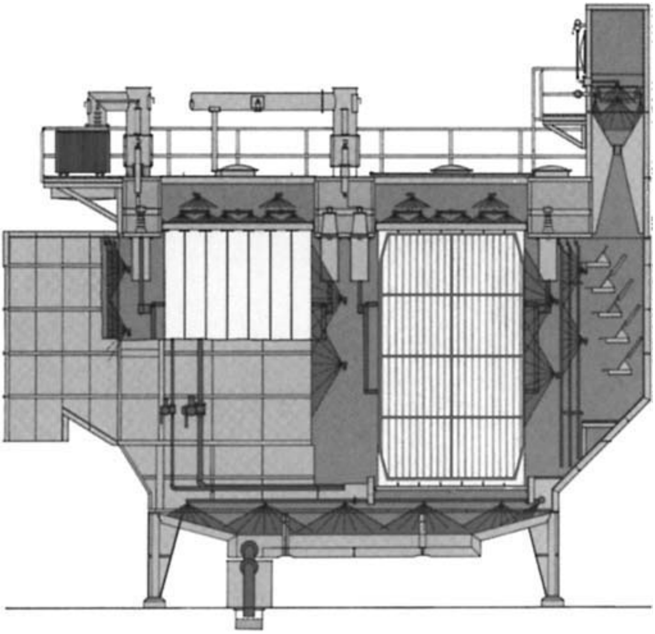


Figure 7.20 Plant-scale wet ESP

Large-scale precipitators such as this are used for gas cleaning with flows ranging from 10 to 500 m^3/s. A large precipitator may be built as one or more casings in parallel, with each chamber comprising several fields in series.

Typically, electrostatic precipitators are powered either by traditional DC-energized thyristor controlled transformer-rectifier sets, or by the pulse system. An increase in the DC voltage applied to the discharge electrodes gives a higher collecting efficiency, but the high voltage may lead to heavy sparking, which then lowers the collecting efficiency. With pulse energization, the precipitator current can be limited to extremely low values despite very high voltages, due to the short duration of the pulses – fixed within the 50 to 200 µs range.

Pulse energized electrostatic precipitators can, for many applications, be of considerably smaller dimensions than a DC-energized precipitator with the same performance. The performance of a DC precipitator can be improved by the addition of a pulse energized system. Typical applications include precipitators for cement kilns, black liquor boilers, clinker grate coolers, flue gas desulphurization, municipal waste incinerators, coal mills and coal-fired power plants.

8

FILTER SELECTION

SECTION CONTENTS

8A. INTRODUCTION

This Handbook has aimed to introduce a new practitioner to the range of filters and related types of equipment, especially those intended for utility service use. For each type, broad indications have been given as to their particular applications, and those recommendations are brought together in this final section. No attempt is made, however, to provide a thorough guide to filter selection: for that, the reader is guided to the book by Richard Wakeman and Steve Tarleton on equipment selection (*Solid/Liquid Separation: Principles of Industrial Filtration*, published by Elsevier Ltd, 2005).

This final part of the Handbook thus includes broad recommendations on filtration equipment employment, and finishes with reference to the standards governing filter testing and performance.

8B. FILTER SELECTION

The selection of a filter must begin with a definition of the job that the filter is required to do – at how fine a particle size is the separation to be made (cut-off point) and how sharp does this cut-off have to be, which will usually define the nature of the filter medium, followed by how much fluid is to be treated with what maximum pressure drop, which will define how much filter medium is required. The decision at this stage is then often between a depth filtration medium and a surface/cake filtering material.

Before these two performance characteristics are defined, it will usually be apparent whether the fluid to be treated is a gas (in which case fluid viscosity can be disregarded) or a liquid (with viscosity now an important process parameter). Filters intended for these two types of fluid are usually very different in design, and the filtration purpose is often very different: gas filtration is almost always required to achieve removal of a relatively low level of contamination, with a relatively low pressure drop, while liquid filtration, in addition to decontamination functions, may have to recover the suspended solid as a valuable process product, and use quite high pressure drops to do so.

The next consideration is usually of how much suspended solid has to be removed per unit time, which in concert with the solids retention (dirt-holding) capacity of the filter medium, will decide the operating cycle time (or, of course, the cycle time may be fixed by some other consideration, so that the dirt-holding capacity will have to match that time requirement).

In the case of a solids recovery process, these considerations of solids loading and throughput rate will usually lead to the proper choice between a batch filter or a continuously operating one. If the feed material is in small batches, then a batch filter will usually be the obvious choice, but a continuous feed of a fairly concentrated suspension can be handled in multiple batch, semi-continuous (i.e. intermittent discharge) or truly continuous machines.

The decision process so far will often have led to the possible choice among a number of different types of filter. This range will then be narrowed by looking at the working position for the equipment – if there is plenty of space available, then perhaps a large, slowly moving filter can be employed, but if space is at a premium (especially where retrofitting is being undertaken) then a much smaller, faster moving centrifuge may be necessary.

Now it is necessary to consider what is to be processed, the fluid and the suspended material, to ensure that the system is compatible with these materials, both the filter medium and the structure of the filter. Of course, if the process fluid is very aggressive (a strong acid or alkali for example, or a gas at 750°C), then this fact should probably have been borne in mind from the start of the selection process.

Last, but by no means least, in this series of decisions, comes the matter of cost, which takes effect at a number of levels. First, there is the capital cost of the equipment, which may be the deciding factor if a tight capital spending budget exists. However, much to be preferred is a cost decision based on lifecycle costs – the sum of the basic machine, plus a lifetime supply of spare parts and a lifetime cost of maintenance. A cheap filter that needs a small fortune spent on it for replacement filter elements should obviously not be chosen over a more expensive machine with long lasting media.

There are still other cost elements needing consideration. If the filter is a retrofit, then there is the cost of moving other equipment to make way for it. More importantly, if the filter is to be installed with a protective function, safeguarding equipment downstream of it, then the cost of failure of the filter to provide this protection must be borne in mind – the extra cost of a filter that will not fail is often less than the cost of disaster.

Apart from the total cost, it is apparent that a great deal of the selection process for a filter is, in fact, based on the selection of a suitable filter medium to effect the actual separation with the required performance. The remainder of this chapter will thus concentrate on media selection, beginning with Table 8.1 which lists the main types of filter media and their characteristics.

Not covered by Table 8.1 are the media made from extruded polymeric fibres, such as spunbonded and meltblown materials. These have proved themselves to be exceedingly good as filter media, with the very small fibre diameters that are possible leading to very low cut-off figures, such that they have taken a major role in ventilation filters. They can be set up as pleated sheets or felts, and they are formable from almost any thermo-polymer, including PTFE.

The selection process

Filter selection is difficult to discuss in general terms, since each application may introduce its own particular problems and these may differ widely from one application to the next. Usually there will also be a number of different types of filter that might be suitable, although specific applications commonly adopt a certain type of filter as the virtual standard, on the basis of proven satisfactory performance, cost, availability and other commercial considerations.

Intake filters on internal combustion engines, for example, are of a more or less standardized design that is mass produced and as a consequence extremely cost-effective. Probably the most significant difference for most of their lives was that a felt filter medium was often preferred for diesels and a paper element for petrol engines. Similarly, in other fields of application, the most suitable type of filter has usually been established by experience, with the products of individual manufacturers differing mainly in detailed design or choice of element material.

Filter performance refers largely to the cut-off achieved by different types of filters. Considerations on such grounds will usually suggest the most suitable types, although not necessarily the most economic solution to the problem. Again, individual assessment of the degree of protection required may vary considerably for a similar application. Some machine tool designers are quite satisfied to achieve protection of the order of 10–20 μm, while others may opt for maximum protection against wear by filtering down to an absolute rating of 5 μm. Much, of course, depends on the application of the machine, and any critical feature of its design or operation. Where finer filtration can save downtime, for example, the additional cost of such filters is more than justified, provided that this can be allied to adequate maintenance. The question is not just a matter of filter selection only, but also proper maintenance of the filters.

Filter rating (cut-off) alone is no absolute criterion. It must be considered alongside filter efficiency and the capital and operating costs of the filter or separator concerned. Also, there are various methods of determining filter ratings and efficiencies. One of the most meaningful figures, and one now widely adopted is the beta rating, associated with the particle size and efficiency figure required.

Table 8.1 Summary of media characteristics

Media	Filter action	Normal minimum cut-off μm	Advantages	Absolute cut-off	Disadvantages	Remarks/typical application
Paper (untreated)	Surface absorbent	10–20	Low cost	No	Very low strength	Simple laboratory filters
Paper (treated)	Surface	5–20	Low cost	No	Low strength (improved by pleating). High specific resistance. Only suitable as surface filters. Subject to element migration.	General purpose compact forms of filters for gases and liquids, also limited application in filter presses for facing filter cloth.
Paper discs	Edge (depth)	Down to 1	Low cost. Adjustable cut-off (by stacking pressure)	Yes	High specific resistance not cleanable.	Fine filtering of gases and liquid.
Fabrics	Surface	Down to 5	Can withstand higher pressures than paper. More suitable for larger sizes of filters.	No	Lack rigidity and normally need to be backed up or supported by a screen, mesh, etc.	Fabrics cover a wide range of materials with varying characteristics. Fabric elements may be used for general purpose gas and liquid filters; also for dust collectors, filter cloths, etc.
Felts	Depth	Down to 10	Mechanical properties can be closely controlled during manufacture. Available in a wide range of materials (mostly synthetic).	No	Lack rigidity so need support.	Thinner felts alternative to paper for pleated elements. Filter pads for a very wide range of industries.

Woven wire	Surface	Down to 6	Performance controlled by weave and mesh. High strength.	Yes	More expensive than cloth or paper	Widely used in coarse, medium and fine mesh.
Mineral wools	Depth	Down to 0.1	High permeability, suitable for ultra-fine filtering with micro-diameter fibres and suitable backing – suitable for high temperatures.	Yes	Asbestos fibres can represent a health hazard. Flow velocities must be kept low. Not particularly suitable for filtering liquids.	Ultra-fine filtering of air and gases.
Glass fibre	Depth	Down to 1 or better	Properties can be controlled and graduated during manufacture. Suitable for high temperatures.			Filter pads or blankets for air filters. Microglass sheets for HEPA filters.
Diatomaceous earth	Depth		Very effective for fine filtering with low resistance.	No	Normally suitable for use only as a precoat, but can be rendered in sheet form with binder.	Precoat filters, particularly suitable for clarifying.
Perlite	Depth		Low wet density. Fine filtering capability with low flow resistance.	No	As for diatomaceous earth, but normally needs to be used in thicker layers.	Precoat filters.
Activated charcoal	Adsorbent	Removes vapours, odours etc.			Granular product, needs containing in a suitable housing.	Final filter for air or water, chemical treatment, etc.

(*Continued*)

Table 8.1 (Continued)

Media	Filter action	Normal minimum cut-off µm	Advantages	Absolute cut-off	Disadvantages	Remarks/typical application
Charcoal cloth	Adsorbent	Removes vapours, odours, etc.	Strong, flexible material with 20 times the adsorbent properties of activated charcoal.		High cost.	Prefabricated filter elements for colour control, air conditioning, water and chemical treatment, etc.
Fuller's earth (activated clays)	Adsorbent				Granular form – needs a suitable container. Less effective than activated charcoal.	Final filters for odour and vapour removal.
Anthracite	Depth		High flow rates possible in multi-layer beds with sand.		Needs to be treated for maximum hardness.	Used in gravity and pressure filters for water treatment and filtering of oils, acids, alkalis, etc.
Sintered metal	Depth	Down to 2	Properties can be closely controlled during manufacture. High strength element. Suitable for high temperatures.	Yes	Possibility of element migration. High cost. Not cleanable.	Sintered bronze for general duties. Stainless steel or exotic alloys for higher pressures, temperatures and corrosion resistance.

Ceramic	Depth	Down to 1	Properties can be controlled during manufacture. Suitable for corrosive fluids. Suitable for high temperatures.	Yes	High cost. Not cleaning.	Particularly suitable for acids, alkalis and other corrosive media.
Membranes	Surface	Down to 0.005	Available in a wide range of materials.	Yes	Require vacuum or pressure source. Low flow rates. Clogged by fibrous or slimy contaminants.	Ultra-fine filtering and clarification in specialized applications.

Filter size

The size of a filter needs to be selected with regard to the acceptable pressure drop and the cycle time required between successive cleaning or element replacement. This is closely bound up with the type of element and filter medium employed. In conditions of heavy contamination, a filter element with high retention properties may clog too quickly for economic use, calling for a much larger size than normal, or alternatively a different type of element with better collecting properties, so that clogging is slowed down. If necessary, the filter may even be given decreasing efficiency properties so that an excessive pressure drop is avoided, at the cost of some loss of protection, but not the complete loss of protection, as would occur with bypass flow initiated at a particular level of clogging.

Surface vs depth media

Surface filters generally have relatively low permeability. To achieve a reasonably low pressure drop through the filter, the element area must be increased so that the velocity of flow through the element is kept low. Given a projected element area, A, and a nominal flow velocity, V, at the design maximum capacity of the filter, pleating or otherwise shaping the element so that its surface area within the same housing volume becomes 10A will reduce the flow velocity through the element to V/10. This is the principle adopted with most surface filters, and also with some thicker media such as felts, which also filter in depth as well as on the surface. With a thicker medium, the increase in surface area possible by pleating or folding is more restricted, so that similar reductions in flow velocity cannot be achieved with the same overall size of element.

By increasing the element area still further, the pressure drop can again be reduced. This is typical of panel-type air filters, where the pressure drop is normally very low. Such a low pressure drop is necessary when dealing with large quantities of air, probably flowing at relatively low or moderate velocities. Appreciable attenuation of the air flow through the filter could adversely affect the performance of the complete air-conditioning system. When handling liquids, on the other hand, pressure drop through the filter is inevitably higher, or tends to be higher, because of the greater velocity (and viscosity) of the fluid. In this case it is more usual for the permissible range of pressure drops to be much more restricted.

Compatibility

Other essential requirements for the filter element are complete compatibility with the fluid and the relating system. Compatibility with the fluid means freedom from degradation or chemical attack, i.e. a chemically compatible element. In the majority of cases this is not a severe problem, as even paper elements may be impregnated or treated so as to be compatible with a very wide range of fluids. At the same time, however, mechanical compatibility is also necessary to ensure that the element is strong enough for the duty involved. It must also be free from fibre migration. This may or may not be a critical factor, because in some systems a certain amount of migration may be tolerated, but in others the fact that fibre migration could occur would eliminate that particular filter element from a list of possibilities.

Whilst mechanical compatibility is largely a matter of system requirements, it can also be affected by the nature of the contaminant. Hard abrasive materials forced against soft media may produce physical damage, opening up localized leakage paths through the element. Similarly collection of fine abrasive particles by a flexible element may abrade and damage that element. Synthetic fibre filter cloths for example are often more prone to damage in this manner than natural fibre.

Contamination levels

The level of contamination in the fluid may also affect the type of filter chosen for a particular duty. Thus an oil bath filter, for example, may be preferred to a dry element in a particularly dust-laden atmosphere, such as an internal combustion engine operating under desert conditions, due to its large dust-holding capacity. Larger or heavier particles are deposited in the oil bath on entry, whilst the scrubbing of the air by the large area of oil-wetted surfaces removes the remaining dust. Dust-laden oil then returns to the bath where dust collects at the bottom displacing oil, which is automatically transferred by an overflow pipe to a lower reservoir, whence it can be reclaimed and reused during the servicing of the unit.

Prefilters

Where fine filtration is required, prefiltering should be considered as advisable, even necessary. Thus, if an air stream is heavily contaminated with particles of say 100 μm and smaller, and if protection of subsequent equipment down to the order of 10 μm or less is required, the filter capable of providing this degree of protection may also become rapidly clogged with coarser particles. If these are removed by prefiltering through a coarser filter or even a strainer, the main filter element performance will be maintained for much longer intervals between cleaning or replacement procedures. In fact, with any type of filter which shows virtually 100% efficiency at a particle size substantially lower than the filtration range required, prefiltering is well worth considering as an economic measure to reduce the dirt load reaching the filter, depending on the level of contamination involved.

Filter selection

Most of the basic types of fluid filter are summarized in Table 8.2 whilst Table 8.3 presents a basic selection guide. It must be emphasized that such a representation can only be taken as a general guide. Particular applications tend to favour a specific type of filter and element or range of elements. The requirements for liquid filters are far more diverse than in the case of air filters since the contaminants may range from sub-micrometre particles, which have to be removed for clarification or polishing, through wear and degradation products in the case of circulatory oil systems, to fibrous and stringy solids in the case of effluents and process liquors. Filtration purposes may vary considerably. Thus, instead of being a contaminant,

Table 8.2 Basic types of fluid filters

Type	Media	Remarks
Surface	(i) Resin-impregnated paper (usually pleated)	Capable of fine (nominal) filtering. Low permeability.
	(ii) Fine-woven fabric cloth (pleated or 'star' form)	Lower resistance than paper. Ultra-fine filtering.
	(iii) Membranes	Coarse filtering and straining.
	(iv) Wire mesh and perforated metal	
Depth	(i) Random fibrous materials	Low resistance and high dirt capacity. Porosity can be controlled/graduated by manufacture.
	(ii) Felts	Provide both surface and depth filtering. Low resistance.
	(iii) Sintered elements	Sintered metals mainly but ceramics for high temperature filters.
Edge	(i) Stacked discs	Paper media are capable of extremely fine filtering. Metallic media have high strength and rigidity.
	(ii) Helical wound ribbon	
Precoat	Diatomaceous earth, perlite powdered volcanic rock, etc.	Form filter beds deposited on flexible semi-flexible or rigid elements. Particularly suitable for liquid clarification.
Adsorbent	(i) Activated clays	Effective for removal of some dissolved contaminants in water, oils, etc. Also used as precoat or filter bed material.
	(ii) Activated charcoal	Particularly used as drinking water filters.

the solids collected by the filter may be the valuable part, which needs to be removed easily, necessitating the use of a type of filter that builds up a cake, which is easily removed. Equally, where the residue collected is of system contaminants, ease of cleaning or replacement of the filter element may be a necessary feature for the filter design.

It is, therefore, necessary to relate basic filtration requirements to possible types of filter and then to study the specific performance of individual designs of filters, of suitable types, against system requirements. In the case of straightforward applications, this generally leaves only a suitable filter size to be selected. Where other or more critical factors are involved, close co-operation between potential user and equipment manufacturer may be necessary in order to arrive at an optimum solution, particularly as regards the choice of medium.

Table 8.3 General selection guide for filters

Element	Sub-micrometre (under 1)	Ultra-fine (1–2.5)	Very fine (2.5–5)	Fine (5–10)	Fine/ medium (10–20)	Medium (20–40)	Coarse (over 50)
Perforated metal							X
Wire mesh							X
Wire gauze						X–X	X
Pleated paper					X–X	X–X	
Pleated fabric						X–X	
Wire wound					X	X–X	
Wire cloth				X	X–X	X–X	X
Sintered wire cloth				X	X–X		
Felt						X–X	
Metallic felt			X	X–X	X–X		
Edge type, paper	X	X–X	X–X	X–X			
Edge type, ribbon element						X	X
Edge type, metal					X	X–X	X
Edge type, nylon				X–X	X–X	X–X	X
Microglass	X	X–X	X–X				
Mineral wool				Limited application for liquids			
Ceramic	X	X–X	X–X	X–X			
Filter cloths				X	X–X	X–X	X
Membrane	X	X–X	X–X				
Sintered metal		X	X–X	X–X	X–X	X–X	
Sintered PTFE				X–X	X–X		
Sintered polythene						X–X	X

Air filters

Air filters, and primarily those intended for ventilation of living and working spaces, are classified by efficiency in the CEN/EUROVENT classification given in Table 8.4. Much depends, in their selection, on the degree of protection required and the volume of air to be treated. Actual requirements can range from normal room protection to the supply of sterile air for critical processes and biomedical applications. For positive protection

Table 8.4 Eurovent and cen classifications of ventilation air filters

Type	Eurovent class	CEN EN779 class	Efficiency (%)	Measured by	Standards
Coarse dust filter	EU1	G1	<65	Synthetic dust weight arrestance	ASHRAE 52–76
	EU2	G2	65 < 80		Eurovent 4/5
	EU3	G3	80 < 90		
	EU4	G4	>90		
Fine dust filter	EU5	F5	40 < 60	Atmospheric dust spot efficiency	BS 6540
	EU6	F6	60 < 80		DIN 24 185
	EU7	F7	80 < 90		EN 779
	EU8	F8	90 < 95		
	EU9	F9	>95		
High efficiency particulate air filter (HEPA)	EU10	H10	85	Sodium chloride or liquid aerosol	BS 3928
	EU11	H11	95		Eurovent 4/5
	EU12	H12	99.5		DIN 24 184
	EU13	H13	99.95		(DIN 24 183)
	EU14	H14	99.995		
Ultra low penetration air filter (ULPA)	EU15	U15	99.9995	Liquid aerosol	DIN 24 184
	EU16	U16	99.99995		(DIN 24 183)
	EU17	U17	99.999995		

against sub-micrometre particles and small particles of up to 5–10 μm, filters capable of an absolute cut-off are essential. This sets specific limits as regards suitable types. However, for less critical applications, a filter with a nominal or mean cut-off in the required range may be satisfactory. Whilst these types do not preclude the possibility of larger particles passing through the filter, the percentage of such particles passed is not likely to be high and may in fact be negligible.

The multi-pass filter test is the normally used method for evaluating filtration performance. It consists of circulating a highly contaminated fluid through the test filter at constant flow rate and temperature. As the filter element picks up contaminant particles, the differential pressure drop across it increases. The test is terminated at a predetermined differential pressure across the filter, and three basic performance characteristics are evaluated: separation efficiency (against particle size), contaminant holding capacity, and clean-assembly flow or pressure drop performance.

The particle separation ability is evaluated for several different particle sizes. This is accomplished by counting the number of various sized particles in fluid samples extracted upstream and downstream of the test filter. These samples are evaluated at several times during the test to establish the change in separation ability as the element traps contaminant. This information is usually presented as β

values for the various particle sizes which are being evaluated. The β value (the ratio of the number of particles of a certain size that were counted in the upstream sample versus that in the downstream sample) is always specified in conjunction with the particle size for which it has been determined. The β value has been accepted as a measure of the true separation efficiency of the filter element, the relation between β and the separation efficiency being:

$$\text{separation efficiency } = 100(\beta - 1)/\beta$$

Some efficiency figures are given in Table 8.5, which shows a number of efficiency values against the ratios to which they correspond.

Table 8.5 Beta ratios

for β ratio	efficiency
1	0
2	50%
10	90%
20	95%
50	98%
100	99%
1000	99.9%
10000	99.99%
100000	99.999%

The validity and usefulness of β values obviously depends on the number of particles present in the fluid sample, the volume of fluid, the counting method and accuracy, and the sample processing technique. Particle counting accuracy and repeatability generally result in a ±2 count variation for any given fluid sample. Accordingly, there is a definite limit, based on the aforementioned factors, at which a difference in β values becomes meaningless. The generally accepted limit for β values, generated with off-line bottle counts, is 75 although with in-line particle counters and sophisticated handling techniques this limit may be lower. Figure 8.1 shows a set of β ratios plotted against the particle sizes to which they correspond, for three different depth filtration media, classified by the particle size for which their β ratio is 100.

Membrane selection

The membrane is still a relative novelty in the filtration business, despite its nearly 50 years of application, so some comments on its selection seem justified. The performance and selection of a membrane are affected by a multiplicity of factors associated with the membrane medium, the particulate material, the fluid carrier phase, the conditions of operation, and the interactions among all these factors. Of particular importance are

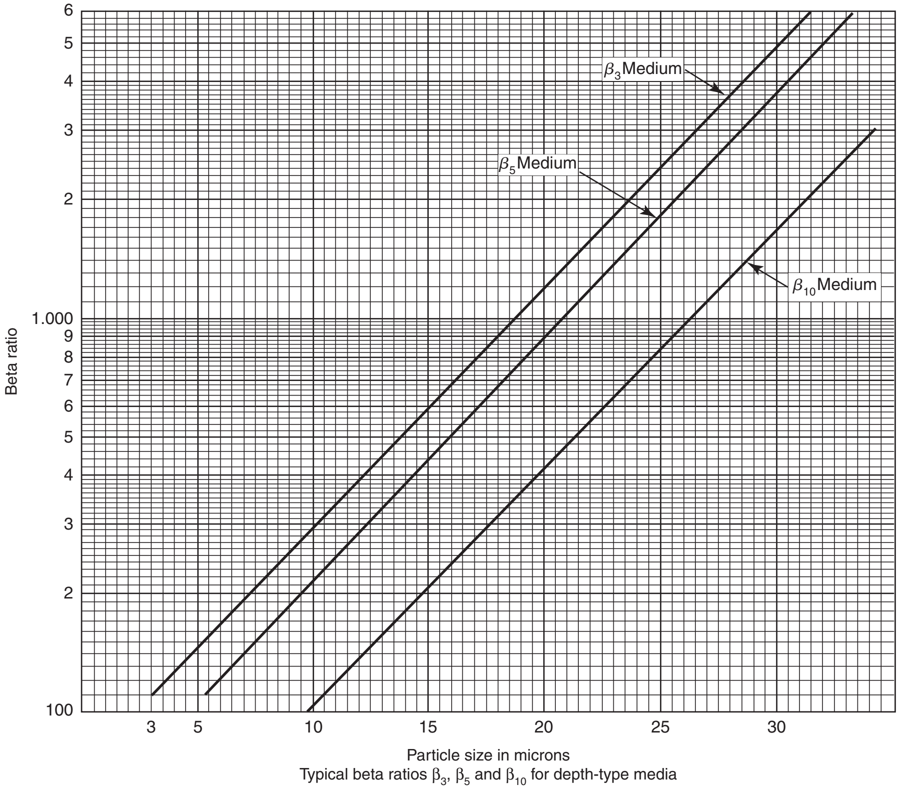


Figure 8.1 Beta ratios *vs* particle size

those that relate to the particulate material (size, shape, concentration, distribution, zeta potential, and whether it is inert or viable), the membrane structure (pore size, rating, asymmetry), the stability of the membrane (chemical, mechanical, thermal, hydrolytic, extractables, shedding), and the retention mechanisms (absorption, adsorption, impingement, cake retention).

The selection of an optimum (or at least an appropriate) membrane and system will usually require a trade-off between various possible alternatives. Table 8.6 summarizes the typical information required to permit a systematic analysis of the available options.

The important performance indicator in membrane microfiltration is the volumetric flow through the membrane, which is directly proportional to the applied pressure difference across it. For most membranes, values of fluid flux are quoted for particular conditions of temperature and applied pressure, with specific fluids, which typically are water, air and methanol.

From the data normally available for membranes, it is possible to calculate the permeability constant for the membrane for a particular fluid. In principle, this

Table 8.6 Membrane filtration selection criteria

Criteria	Characteristics
Fluid Properties	What liquid or gas is being filtered? What are of the fluid properties (pH, viscosity, temperature, surface tension, stability etc.)? What are the important chemical components and their concentrations? What pretreatment has been given to fluid? What is the desired minimum and maximum flow rate? What is the product batch size?
Pressure Characteristics	What is the maximum inlet pressure? What is the maximum allowable differential pressure? Is there a required initial differential pressure? What is the source of pressure (centrifugal\positive displacement pump, gravity, vacuum, compressed gas etc.)?
Sterilization\Sanitization	Will the filtration system be steamed or autoclaved? Will the system be sanitized with chemicals or hot water? How many times will the system be sterilized or sanitized? What are the sterilized\sanitization conditions?
Hardware	Is there a restriction on the material for the housing? Is there a recommended housing surface finish? What are the inlet and outlet plumbing connections? Is there a size or weight restriction?
Filter	What is the size of particles to be retained? Will the filter be integrity tested; if so, how? Will this be a sterilizing filtration? Is there a minimum acceptable level of particle removal? Is there a recommended filter change frequency?
Temperature	What is the temperature of the fluid. Temperature affects the viscosity of liquids, the volume of gases and the compatability of the filtration system
Configuration	How will the filtration systems be configured – in series or in parallel. *Parallel flow arrangement*: uses several filters of equal pore size simultaneously to either increase flow rates, extend filter service life or lower differential pressure. It also permits filter changeout without system shutdown. The total flow rate and differential pressure is equally distributed across each filter. For any given flow rate, the differential pressure can be reduced by increasing the number of filters in parallel. *Series flow arrangement*: uses a group of filters of descending pore sizes to protect the final filter when the contaminant size distribution indicates a wide range or a high level of particulates that are larger than the final pore size. You can also use additional filters of the same pore size in series to improve particle removal efficiency, to protect against the possible failure of a unit within the system, and to add an extra measure of safety in any application.

should be independent of the fluid if there are no interactions between the membrane and the feed slurry. The important factor in microfiltration is not the flux of clean fluid but the performance during actual filtration. Performance is potentially affected by several solute-related parameters and specifically by concentration polarization and fouling.

Microfiltration membranes are routinely used in a range of analytical procedures to determine particulate contamination in a wide range of gases and liquids. The procedures include the detection of micro-organisms in a variety of waters and process fluids (foods, beverages, pharmaceuticals) where the membrane traps the micro-organism and is subsequently used as the culture medium, in passive cell growth studies and in so-called blotting applications. A range of different types of membrane is used, including:

1. mixed cellulose esters – e.g. biologically inert mixtures of cellulose acetate and cellulose nitrate; suitable for a wide range of analytical procedures, including gravimetric analysis by the ashing technique and light microscopy
2. PTFE – either unlaminated or laminated to a support of high-density polyethylene or polypropylene; for applications with gases and non-aqueous fluids, with acids and alkalis, and for higher temperature operation
3. silver – ideal collection medium for analysis of crystalline silica by X-ray diffusion and for the analysis of organics
4. PVDF – suitable for aqueous or organic samples, and
5. track-etched polycarbonate – recommended for scanning and transmission electron microscopy.

Commercial polymeric ultrafiltration membranes are designed to give the requirement of high permeability and high permselectivity. An extensive range of membrane materials is used including polysulphone, polyethersulphone, PAN, polyimide, cellulose acetate, aliphatic polyamides, the oxides of zirconium and aluminium, and other ceramics. Membranes are produced as flat sheets, also used as spiral wound modules, and in tubular or hollow fibre forms.

The flux of the liquid through ultrafiltration membranes is much smaller than through microfiltration membranes, in the general range of 0.1–10 m^3/day, the actual figure depending upon many structural parameters. For pure water (or other liquids) there is a linear correspondence between flux and transmembrane pressure. With solutions there is a tendency for the flux to reach an asymptotic value with increasing pressure. This is a result of several factors, including concentration polarization, gelation, fouling and osmotic effects.

The selection of a membrane for ultrafiltration will require determining the molar mass of the species to be separated and selecting a membrane with a limiting rejection under anticipated conditions of operation. Small-scale application tests will generally need to be performed. Ultrafiltration membranes are rated in terms of their nominal Molecular Weight Cut-off (MWCO). There are no industry-wide standards for this rating, hence manufacturers use different criteria for assigning ultrafiltration pore sizes. For example, for the concentration of protein, the protein should be larger than the MWCO of the membrane by a factor of 2–5. The greater the difference (i.e. the tighter the membrane pore size), the higher the protein yield. The protein shape, in addition to its molecular weight, plays a role in determining its retention by the membrane. The more globular the protein, the greater its retention, while linear proteins may require a tighter membrane for high recoveries. Moreover, protein shape may be affected by solution pH or salinity.

Although the separation mechanism of ultrafiltration is broadly considered to be one of sieving, in practice the effect of concentration polarization limits the flux, due to a build-up of solute in the concentration boundary layer on the feed side of the membrane. At sufficiently high pressures, gelation of the macromolecules can occur, resulting in the formation of a thin gel layer on the surface; this can act as a secondary membrane. Increasing the feed stream circulation rate will generally reduce the thickness of the gel layer and increase the flux. Operation within the turbulent flow regime may significantly enhance permeation by reducing the thickness of both the gel and fouling layers, by transferring solids from the membrane surface back into the bulk stream. As with microfiltration, factors of chemical compatibility of materials with the solution will need to be addressed.

8C. REFERENCE STANDARDS

Standards exist for many parts of the filtration business, but especially for the critical fluid services such as engine inputs, lubrication, hydraulics and ventilation. They may be discovered by a search of the indices of the various standards publications bodies (for example in www.bsi-global.com/for the British Standards Institute).

There is a wide range of coverage of both gas and liquid applications, although the publication process is by no means complete, nor is the revision of standards in rapidly developing fields. Some standards, of course, are vital and broad-ranging, such as the BS EN 1822 series on HEPA and ULPA filters, or EN 779 for the determination of the performance of particulate air filters.

Standards are grouped by their originating authority: BS for British standards, EN for the European standards office, and ISO for the international standards organization (into the last of which all other national or regional standards are very slowly being included). The specification number is usually completed by the year of issue.

Where a standard is common to more than one source, the organizational letters are combined (as in BS EN 1822). Other important sources are ASHRAE in the USA (especially as in the ASHRAE 52 series for ventilation filters) and VDI in Germany (for example, VDI 3926 on cleanable filter media).

Little is to be gained by attempting a complete listing of filtration-related standards – the reader is firmly directed to search the publications list on the BSI web site quoted above. However, some selected standards can be identified so as to give an indication of what is to be found.

The range is from terminology:

BS EN ISO 14644-6:2007, Cleanrooms and associated controlled environments. Vocabulary

BS ISO 16232-8:2007, Road vehicles. Cleanliness of components of fluid circuits. Vocabulary

Through general techniques:

BS ISO 11171:1999, Hydraulic fluid power. Calibration of automatic particle counters for liquids

BS 7591-4:1993, Porosity and pore size distribution of materials. Method of evaluation by liquid expulsion

BS EN 60970:2007, Insulating liquids. Methods for counting and sizing particles

To specific methods:

BS ISO 3724:2007, Hydraulic fluid power. Filter elements. Determination of resistance to flow fatigue using particulate contaminant

BS 4552-1:1979, Fuel filters, strainers and sedimentors for compression-ignition engines. Methods of test

BS 7403-2:1998, ISO 4548-2:1997, Full-flow lubricating oil filter for internal combustion engines. Method of test for element bypass valve characteristics.

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