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Solid-Liquid Filtration and Separation Technology

Second, Completely Revised Edition

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Preface to the Second Edition

The pace of technological development continues and no aspect is free from change. The period since the first edition went to press has seen much new work published in the field of filtration and separation so it was felt important to introduce a revised and up to date version of this text. The first edition was warmly received and kindly reviewed, for which comfort the authors are particularly grateful, but inevitably there were some imperfections and shortcomings evident. So the authors are doubly grateful for this opportunity to present a revised and refreshed edition.

Highlights of this second edition include a major revision and updating of the chapters dealing with the fundamental processes of filtration and sedimentation. Full details are provided on how to simulate the formation of filter compacts and sediments, including compressible compacts and sludges in consolidation tanks. New pictures, illustrations, descriptions and applications of the process equipment are included. Information to create the simulation models in a computer spreadsheet package is contained within the relevant chapters, and the World Wide Web address is provided to allow the relevant files to be downloaded at no further cost.

Extensive revision of the section on crossflow membrane microfiltration includes discussions of emerging applications such as the removal of cryptosporidium oocysts from drinking water. A new section concerns the design of microfilter membranes to minimise fouling and information on the use of critical flux strategy to avoid permeate flux decay.

The role of surfactants in coagulation and flocculation is included and the extended DLVO theory, which usefully explains some anomalies, is introduced. Applications of surfactants and other surface effects such as that of zeta potential are discussed in relation to sedimentation and flotation.

The chapter on process equipment and calculations has been revised and extended to include further analysis of filtration economics.

There are many new diagrams, tables and photographs throughout the book.

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January 2000

Preface to the First Edition

The separation of particulate solids from Liquids by filtration and associated techniques constitutes an important and often controlling stage in many industrial processes. The latter generate a somewhat bewildering array of particle-fluid separation problems. Separation by filtration is achieved by placing a permeable filter in the path of the flowing suspension. The barrier, i.e. a filter screen, medium or membrane in some cases is selected with a view to retaining the suspended solids on the filter surface, whilst permitting passage of the clarified Liquid. Other systems, e.g. deep-bed or candle filters, operate in a different mode, in promoting deposition of the particles within the interstices of the medium. Further purification of the clarified liquid may proceed by the use of adsorbents to remove dissolved solutes. Alternatively, the two phases may be separated by sedimentation processes, in the presence of gravitational or centrifugal force fields.

Serious operational problems centre on the interaction between the particles and the filter medium. Plugging of the latter, or collapse of the collected solids under the stress caused by flow through the filter, can result in low productivity. Such effects are often related to the size of particles being processed; enhanced effective particle size can be accomplished by pretreatment with coagulants or flocculants. These techniques are discussed in detail in the text, which also reports recent improvements in the machinery of separation, e.g. the variable chamber presses, the cross-flow processes, ceramic dewatering filters, etc.

Several of these newer modifications in filtration plant have followed trends in the developing science of solid–fluid separation and the growing understanding of the processes involved. Fortunately, filtration processes have attracted the attention of increasing numbers of scientists and engineers. A large output of literature has resulted in a copious flow of design and operational information sufficient to place filtration on a much sounder scientific basis.

Nevertheless, the random nature of most particulate dispersions has resulted in a wide range of machines in this unit operation. Selection of the best available separation technique is, therefore, a difficult process problem. It is the authors' viewpoint that many existing separation problems would have been avoided by the application of available scientific data. This text is aimed at the provision of theoretical and practical information which can be used to improve the possibility of selecting the best equipment for a particular separation. It is relevant to record the recent increased commercial awareness of the need for this information in the selection of plant used in environmental control.

The material presented in the text has been used by the authors in short-course presentations over several years. These courses are illustrated by a large number of practical problems in the SLS field; some of these problems have been used to illustrate the book.

Basic theoretical relationships are repeated in those chapters dealing with process calculations. This feature minimises the need for back-referencing when using the book.

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January 1996

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1.1 Introduction

It is difficult to identify a large-scale industrial process which does not involve some form of solid-fluid separation. In its entirety, the latter activity involves a vast array of techniques and machines. This book is concerned only with those parts of this technological diversity which relate to solid-liquid separation (SLS).

Attempts have been made [Svarovsky, 1981] to catalogue the variety of processes and machines used in SLS systems; these are usually based on two principal modes of separation:

1. Filtration, in which the solid-liquid mixture is directed towards a "medium" (screen, paper, woven cloth, membrane, etc.). The liquid phase or filtrate flows through the latter whilst solids are retained, either on the surface, or within the medium.

2. Separation by sedimentation or settling in a force field (gravitational, centrifugal) wherein advantage is taken of differences in phase densities between the solid and the liquid. The solid is allowed to sink in the fluid, under controlled conditions. In the reverse process of flotation, the particles rise through the liquid, by virtue of a natural or induced low "solids" density due to attached air bubbles.

The large range of machinery shown in Figure 1.1 reflects the uncertainty which attaches to the processing of solids, particularly those in small particle size ranges.

The filterability and sedimentation velocity of such mixtures depend on the state of dispersion of the suspension; in turn, the latter is strongly influenced by solid-liquid surface conditions which govern the stability of the mixture and the overall result of particle-particle contact. The properties of such systems may also be time dependent, with filterability and settling rate being a function of the history of the suspension [Tiller, 1974].

The dispersive and agglomerative forces present in these systems are functions of pH, temperature, agitation, pumping conditions, etc. all of which complicate the situation and produce the result that suspension properties cannot be explained in hydrodynamic terms alone. Despite these formidable problems, modern filtration and separation technology continues to produce separations in seemingly intractable situations, and to eliminate the "bottle neck" characteristic of the SLS stage in many processes.

A first step in the rationalisation of such problems is to choose the most appropriate technology from filtration, sedimentation or a combination of these two operations. In general, sedimentation techniques are cheaper than those involving filtration; the use of gravity settling would be considered first, particularly where large, continuous liquid flows are involved [Pierson, 1981].

A small density difference between the solid and fluid phases would probably eliminate sedimentation as a possibility, unless the density difference can be enhanced, or the force field of gravity increased by centrifugal action. Such techniques for enhancing sedimentation would be retained as a possibility in those circumstances where gravity separation proves to be impossible, and the nature of the particulates was such as to make filtration "difficult". The latter condition would ensue when dealing with small, sub-micron material, or soft, compressible solids of the type encountered in waste water and other effluents. Some separations require combinations of the processes of sedimentation and filtration; preconcentration of the solids will reduce the quantity of liquid to be filtered and, therefore, the size of filter needed for the separation.

Having decided upon the general separation method, the next stage is to consider the various separational techniques available within the two fields. These operational modes may be listed as:

A Sedimentation: gravity; centrifugal; electrostatic; magnetic
B Filtration: gravity; vacuum; pressure; centrifugal

Another serious consideration, also indicated in Figure 1.1, is whether the separation is to be effected continuously or discontinuously; the latter method is known as "batch" processing. In this case, the separator acts intermittently between filling and discharge stages. The concentration of solids in the feed mixture and the quantities to be separated per unit time are also factors which affect the selection procedure.

This activity is made more complicated by the fact that the separation stage rarely stands alone. Figure 1.2 [Tiller, 1974] includes various pre- and post-treatment stages which may be required in the overall SLS process. Thus, the settling rate of a suspension, or its filterability, may require improvement by pretreatment using chemical or physical methods. After filtration, wet solids are produced, and these may require further processing to deliquor, i.e. reduce the liquid content in the filter cake; in some cases, the latter, being the principal product, requires purification by washing with clean liquid.

It will be apparent that in the development of a typical process for: (a) increasing the solids concentration of a dilute feed, (b) pretreatment to enhance separation characteristics, (c) solids separation, (d) deliquoring and washing, many combinations of machine and technique are possible. Some of these combinations may result in an adequate, if not optimal, solution to the problem. Full optimisation would inevitably be time consuming and expensive, if not impossible in an industrial situation. Certain aspects of filter selection are considered at the end of this chapter and in Chapter 11, on pressure filter process calculations.

1.2 The Filtration Process

As stated above, a typical medium for the filtration of coarse materials is a woven wire mesh which will retain certain particulates on the surface of the screen. As the size of the

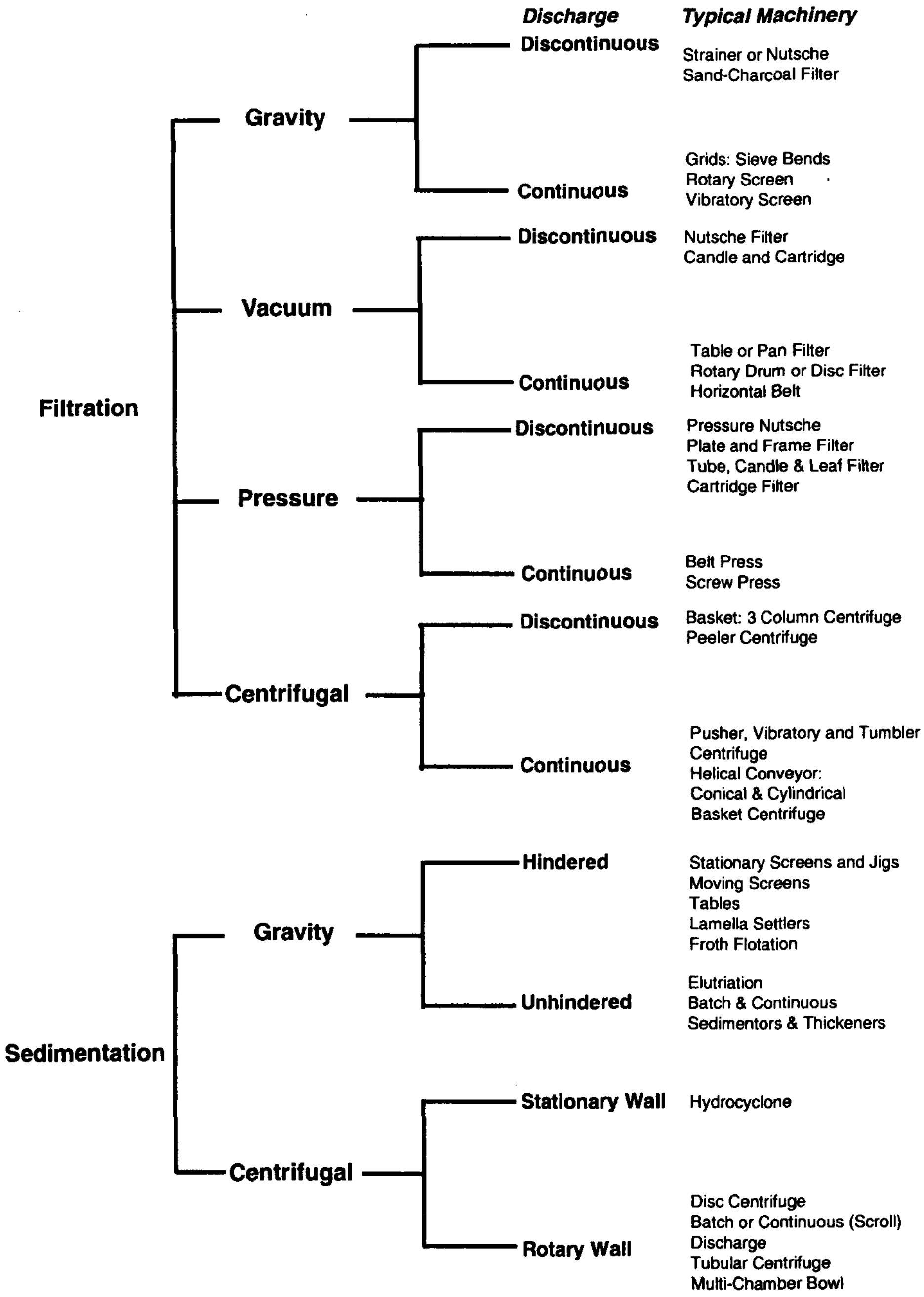

Figure 1.1 General classification of SLS equipment

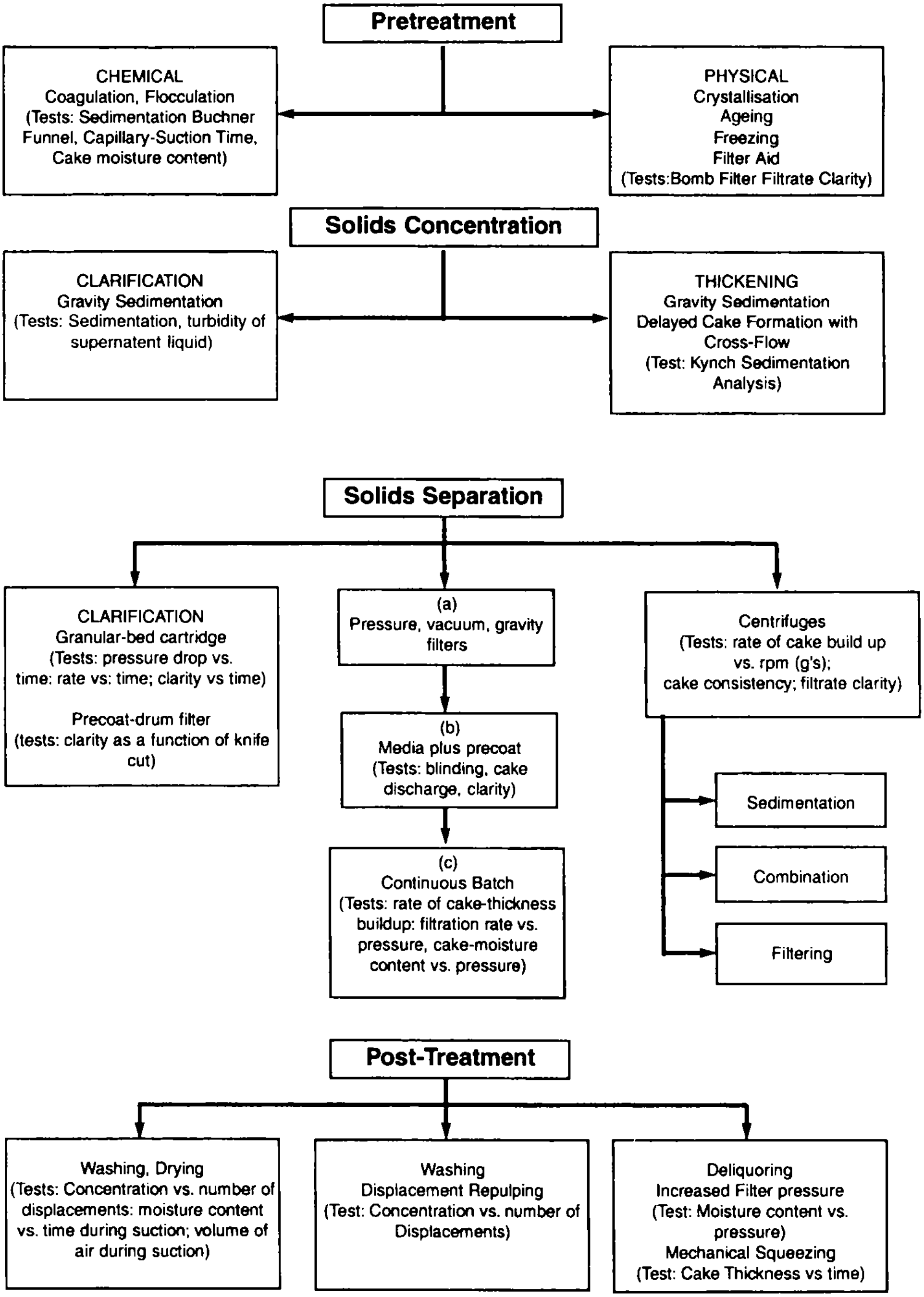

Figure 1.2 Stages and methods of SLS [Tiller, 1974]

particulates decreases, other "screens" are required, e.g. woven cloths, membranes, etc.; these are constructed with smaller and smaller openings or pores. Flow through such a system is shown in Figure 1.3. Where the particulates are extremely small and in low concentration, deposition may occur in the depths of the medium, such as in water clarification by sand filters.

The filtration medium may be fitted to various forms of equipment which, in turn, can be operated in several modes. Thus, plant is available which creates flow by raising the fluid pressure by pumping, or some equivalent device. Such "pressure" filters operate at pressure levels above atmospheric; the pressure differential created across the medium causes flow of fluid through the equipment. Plant of this type can be operated at constant pressure differential or at constant flow rate. In the latter case, the pressure differential will increase with time whilst at constant pressure, liquid flow rate decreases with time.

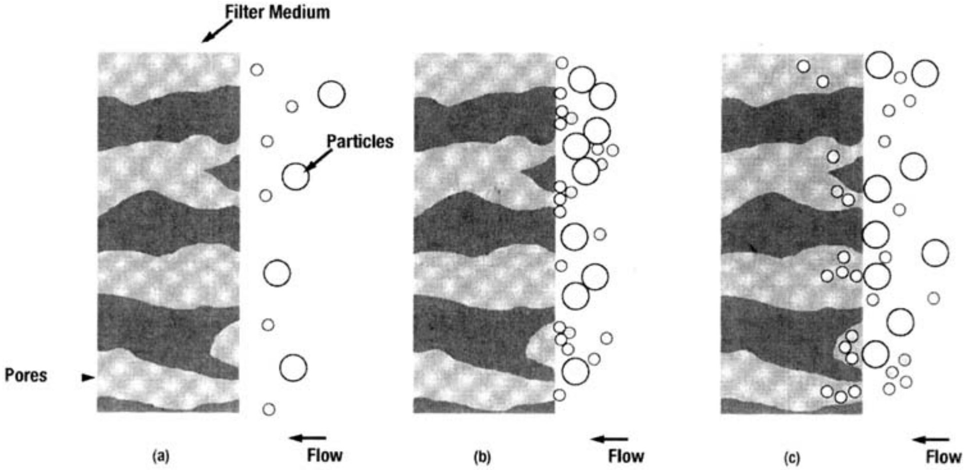

Figure 1.3 Particle deposition in filtration

Subatmospheric, vacuum operation is used in a wide number of applications. In these filters, the absolute pressure downstream of the filter medium is maintained at a low, controlled level by vacuum pumps. The suspension supplied to the filter is delivered at essentially atmospheric pressure; this process is an example of "constant-pressure differential" filtration. Vacuum operation is, of course, a special case of pressure filtration. Here a relatively small pressure differential is available, and attention should be given to pressure losses, e.g. in the frictional effects caused by filtration flow in associated pipes and fittings. Low-pressure conditions in a flowing fluid may lead to the phenomenon of "cavitation" in which dissolved gases, or vapour bubbles, are released into the liquid. Passage of such mixtures through a downstream higher pressure zone, e.g. at the outlet of a pump, causes bubble collapse and material damage to the pump.

Vacuum filters find applications in many areas of industry and are widely used in laboratory tests; the latter are required in order to assess the filterability of the suspension and the suitability of a filter medium. Whilst a complete quantitative description of the SLS process will be described later, at this stage it is sufficient to record that the rate of flow of fluid, at a particular pressure differential, will depend on the resistance to fluid flow of the particles and the filter medium.

Flow can also be created by spinning the suspension, thereby creating a centrifugal force in the system. Thus, centrifugal filters, fitted with suitable filter media are found in many applications in the food, beverage, and pharmaceutical industries.

1.3 Filtration Fundamentals

An understanding of the physical mechanisms involved in SLS is essential in resolving problems developed in existing machinery, or in avoiding future difficulties when selecting new plant. Many years of consultative practice [Purchas, 1987] in this area leads to a realisation of the value of sound quantitative relationships between variables such as liquor flow rate and viscosity, particle size and concentration, filter medium pore rating and their effects on the filtration process.

As mentioned in the previous section, the separation stage is rarely required in isolation and is often followed by drying or dewatering of the porous deposits and/or purification of the recovered solids by washing. Pre- and post-treatment processes such as flocculation, coagulation and liquid expression, may have equivalent process importance in determining, sometimes controlling, the overall separation process time. It is vital to identify process time requirements of the various phases involved in a separation, in order to identify possible bottlenecks. Many examples could be quoted of installed filters with which it is impossible to meet process specifications, and this particularly applies to systems with stringent dewatering and washing requirements. This points to the need for well-designed pilot filter trials, preferably on a small-scale version of the machine of interest, before plant selection. It is, perhaps, unfortunate that such information is not always available, and selection has to proceed with relatively meagre data.

A successful selection procedure is closely linked to the proper choice of the medium to be used in the separation. A large proportion of industrial-scale process difficulties relate to the interaction between the impinging particles and the pores in the filter medium, as depicted in Figure 1.3. The ideal circumstance, where all separated particles are retained on the surface of a medium is often not realised; particle penetration into cloth or membrane pores leads to an increase in the resistance of the medium to the flow of filtrate. This process can ensue to the level of total blockage of the system. Such difficulties can be avoided, if the pores in the medium are all smaller than the smallest particulate in the mixture processed, as discussed below.

The theoretical and practical considerations required for effective SLS are expounded in detail in the various chapters of this book. Of particular importance are the fundamental aspects presented in Chapter 2. Here, the "surface deposition" mode depicted in Figure 1.3 B is described by two series resistances to fluid flow:

a) The resistance of the filter medium R_m
b) The resistance of the particulate layer or "cake" R_c

As obtained in the flow of fluids through pipes and conduits, 'laminar' conditions will be produced by media containing small pores. In these cases, the filtrate velocity v_o through the clean filter medium is proportional to the pressure differential ΔP imposed over the medium; the velocity is inversely proportional to the viscosity of the flowing fluid μ and the resistance of the medium. These relationships may be expressed mathematically as:

$$v_o = \Delta P / \mu R_m \tag{1.1}$$

Under the same overall pressure differential, the filtrate velocity, after the deposition of particles, decreases to v_f where:

$$v_f = \Delta P / \mu (R_c + R_m) \tag{1.2}$$

These simple expressions are developed further in Chapter 2, to include, inter alia, particle concentration effects, filter cake compression, etc.

The equations above are based on the assumption that the medium resistance does not change during the process. This assumption is considered in depth in Chapter 4, where the influence of the filter medium is explained. Generally, R_m takes low values for open, coarse media, e.g. woven screens; the largest media resistances are found in membranes, used in microporous filtration, ultra filtration and reverse osmosis. The filter media resistances in the latter may be one million times higher than those characterising open screens. Those inherent features of these media which can be used to remove very fine particulates, are reported in detail in Chapters 6 and 10 on membrane technology.

Filter cake resistances vary over a wide range, from free filtering sand-like particulates to high resistance sewage sludges. Generally, the smaller the particle, the higher will be the cake resistance. The latter is sensitive to process changes in slurry concentration, fluid velocity, fluid pressure, temperature, etc. These effects have received much attention [Shirato and Tiller, 1987] in the development of physical and mathematical models of the SLS process.

As mentioned above, post-treatment deliquoring and washing of filter cakes are subjects of great importance in SLS operations. These subjects are fully discussed in Chapter 9. A principal interest in deliquoring wet cakes lies in the economic difference between solids drying by thermal and mechanical methods. Thermal drying costs can be much higher (20-30 times) than costs incurred by mechanical dewatering. Dewatered solids are more easily handled than wet sludges; this is of particular importance in waste water treatment processes. A high solidity in a dewatered filter cake can reduce handling costs and improve the possibility of continuous processing.

In filter cake washing, an important aspect is the time (or wash volume) required to remove residual impurities. Quite often, washing may be the controlling step in overall filtration cycles, as discussed in Chapter 9.

1.4 Sedimentation Processes

In certain circumstances, process conditions preclude the possibility of using direct filtration as a means of separating a solid-liquid mixture. High dilution or extreme fineness of particle lead to uneconomic sizes of filter or, in some cases, make normal filtration impossible without pretreatment or concentration of the feed.

Obviously, any device which, at relatively small cost, reduces the absolute amount of liquid in the feed finds application in processes involving large tonnages. Thus the ubiquitous thickener, used for increasing the solids concentration in dilute feeds, is found in almost every section of process industry.

Here, gravity sedimentation, involving a difference in density between solids and liquids, is used to produce an essentially clear overflow of liquid and a concentrated underflow of the mixture. The latter may now be more readily filterable, or be in a condition suitable for disposal, e.g. in sewage handling. Thickeners are used extensively in hydrometallurgical applications, singly or in series, e.g. in counter-current decantation (washing) plants. Where gravity forces lead to inordinately long settling times, the latter may be reduced by chemical treatment, i.e. flocculation and coagulation, as discussed below.

Mathematical analysis of the sedimentation process starts with the well-known Stokes relationship for the setting velocity of a single particle in an infinite expanse of fluid:

$$u_t = x^2 g (\rho_s - \rho)/18\mu \tag{1.3}$$

where u_t is the Stokesian gravitational settling velocity, m/s; x is the particle size, m; g is the acceleration of gravity, m/s^2; ρ_s, ρ are the densities of the solid and fluid, respectively, kg/m^3 ; μ is the viscosity, Pa s. This fundamental relationship must be modified in applications to practical designs of equipment, as shown in Figure 1.4, to allow for the effects of particle concentration on the settling velocity of the suspension U_o.

In general, increases in sludge concentration C lead to decreases in U_o; it follows that the calculation of thickening processes, involving large increases in solids concentration, requires information on the U_o - C relationship. The overall intention in these processes is to produce an overflow of clarified water and an underflow of concentrated sludge.

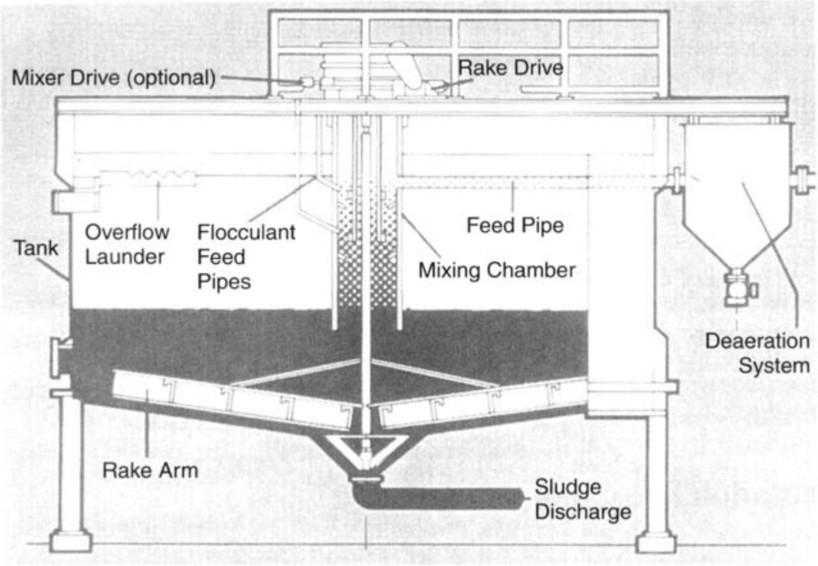

Figure 1.4 High-capacity thickener (Eimco Process Equipment Co. Ltd., United Kingdom)

Suspensions which possess unique U_o- C relationships are termed "ideal"; other mixtures, e.g., biosuspensions, may exhibit "non ideal" settling characteristics where settling rate may be affected by suspensions height, sedimentation column diameter, intensity of mixing before settling, etc. Such suspensions are often described by equations of the type:

$$U_0 = k C^{-m} \tag{1.4}$$

where k relates to the settling velocity at low concentrations. Both k and m vary widely from suspension to suspension. Equation 1.4 indicates that the settling velocity of a suspension is inversely proportional to the solids concentration.

Fundamental aspects of the above processes are considered in detail in Chapter 3. Appropriate tests are required to measure the effect of changes in concentration on U_o. It may be observed that since the downward flux of solids in a settling suspension equates to the product of U_0 and C, the possibility of a minimum flux presents itself. Identification of such minima is required in the specification of process plant used for sedimentation and thickening.

Modern sedimentors are sometimes fitted with inclined plates, spaced at intervals, as shown in Figure 1.5. Theoretical aspects of settlement under inclined surfaces are presented in Chapter 3; practical details of the design of such equipment are dealt with in Chapter 7. Gravity sedimentors compete with devices such as sedimenting centrifuges, hydrocyclones, flotation cells, in the process area of fluid clarification and solids concentration.

Along with the selection of filtration machinery, attempts have been made to provide a basis for the selection of sedimentation equipment [Wakeman, 1994]. Table 1.1 contains some of this information, in abridged form which points to the principal factors influencing such selections.

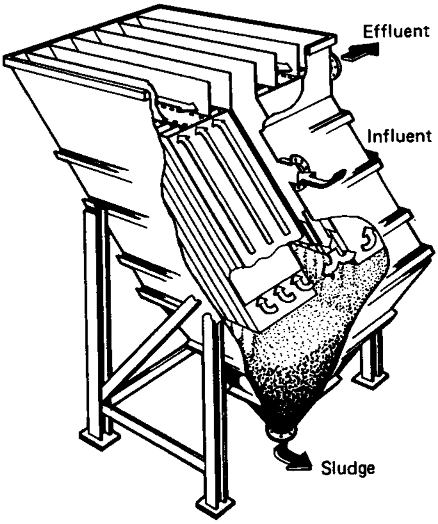

Figure 1.5 Lamella clarifier/thickener (Svedala, Pumps & Process AB, Sala, Sweden)

Table 1.1 Selection of sedimentation machinery [Wakeman, 1994]

	Gravity sedimentation	Sedimentation centrifuges			Hydrocyclones	Flotation
		Tubular bowl	Disc	Scroll		
Scale of process m^3/h	1–(>100)	1–10	1–(>100)	1–(>100)	1–(>100)	10–(>100)
Solids settling rate, cm/s	0.1–(>5)	(<0.1)–5	(<0.1)–5	(<0.1)–(>0.5)	0.1–(>0.5)	(>0.2)
Operation C: Continuous B: Batch	B or C	B	B or C	B or C	C	C
Process * Objectives	a,b,c	a,b	a,b	a,b	a,b,c	a,b

* a: clarified liquid; b: concentrated solids; c: washed solids

1.5 Filter Media

The importance of the filter medium in SLS processes cannot be overstated. Whilst any of the filters reported in this text would deal with most solid–liquid suspensions, albeit with low efficiency in some cases, attempts to use inadequate filter media will incur certain failure. It follows that much attention has been given, in the relevant literature, to the role of the medium in SLS processes.

A wide variety of media is available to the filter user; the medium of particular interest will, of course, be of a type which is readily installed in the filter to be used in the process. Thus woven and nonwoven fabrics, (Figure 1.6) constructed from natural or synthetic fibres, are often used in pressure, vacuum and centrifugal filters. Again, these units can be fitted with woven metallic cloths, particularly in those circumstances where filter aids will be used in the process. The same materials, and also rigid porous media (porous ceramics, sintered metals, woven wires, etc.), can be incorporated into cartridge and candle filters. In these applications, the rigid medium will usually be fashioned into a cylinder, although other shapes exist. Random porous media (sand, anthracite, filter aids) will be used in clarification processes. These generalisations can also be extended to flexible and rigid membranes described in Chapter 10.

The filtration mechanisms involved in separations using such media will depend mainly on the mode of separation. Thus in "cake" filtration, ideally, impinging particles should be larger than the pores in the medium. Experience shows that less processing difficulty is experienced in circumstances where media pores are much smaller than the particles. Despite the obviously higher fluid flow resistance of clean tighter media, in practice, the eventual, used medium resistance will be more acceptable.

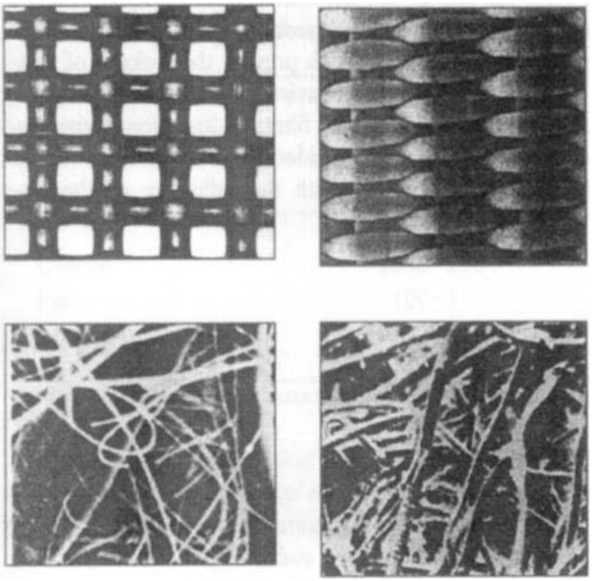

Figure 1.6 Woven and nonwoven filter media

In clarification systems involving depth filtration, loose media are used which are often associated with pores thousands of times larger than the particles requiring filtration. However, deposition of the moving solids onto the medium does occur, and clarified liquids are obtained. Such separations depend on the surface condition and area of the media used in deep-bed systems.

Chapter 4 explores some of the features of filter media, particularly those of the woven fabric variety. The chapter is aimed at developing an understanding of the steps required in media applications to attain process features such as:

(a) clear filtrates
(b) easily discharged filter cakes
(c) economic filtration times
(d) absence of media "blinding"
(e) adequate cloth lifetime

Filter media behaviour is also reported in other sections of the text, e.g. Chapter 10 deals with the crucially important area of membrane separations. Again, Chapter 6 deals with depth filtration systems such as deep sand filters and cartridges, and describes the media used in such equipment.

Some aspects of media selection are also covered in the sections of Chapter 2 which highlight laboratory test procedures. Certainly much can be gained from well-designed laboratory tests in filter media selection. It will also be realised that a vast reservoir of experience and information is available from filter media manufacturers who, fortunately, continue to report their knowledge in the filtration literature.

In this respect, it is interesting to note the newer developments in this subject. Thus in systems where the SLS process calls for filtration and deliquoring of the filtered solids, modern media are available (in woven and ceramic form) which prevent the leakage of gases through the system. Thus Figure 1.7 shows the different behaviour of a modern ceramic "capillary control" medium, which allows the free flow of liquid during filtration and dewatering, but prevents the flow of air used in the last step. This leads to considerable economies in vacuum production [Anlauf and Müller, 1990].