LIQUID-SOLID FILTRATION

INTERNATIONAL SYMPOSIUM

ORGANIZED BY

KONINKLIJKE VLAAMSE INGENIEURSVERENIGING

and

SOCIETE BELGE DE FILTRATION

198th Event of the European

Federation of Chemical Engineering

6 - 7 June 1978

Antwerp – Belgium

SYMPOSIUM PROCEEDINGS

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TABLE DES MATIERES

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RATIONALISING THE SELECTION & SIZING OF SOLID/LIQUID SEPARATION EQUIPMENT

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Introduction

The wording of the title of this paper combines, but also distinguishes between, two distinctive yet interacting activities: SELECTING, from an immense and bewildering variety, the type of equipment best suited to a given application; and DECIDING THE SIZE of this selected type. It is fair to argue that a tacit admission of the difficulty of taking full account of these two activities, and of the many factors which lie behind them, can be seen in the common reference to solid/liquid separation "problems", as compared with the "duties" or "specifications" for operations such as pumping or heating.

It is certainly true that frequently the selection/sizing procedures which result in the installation of a particular SLS device are far less rational than those underlying adjacent pieces of equipment, such as pumps, distillation columns, reactors and heat exchangers. In the process equipment field as a whole, the more avant-garde chemical engineer may reasonably complain that he is still bogged down by an antiquated Meccano tradition, unnecessarily restricted by items listed in manufacturers' catalogues instead of being free to apply sophisticated modern knowledge and techniques to generate an optimum overall design. As a generalisation, there is more than a grain of truth in this view; but especially is it applicable to solid/liquid separation, where often decisions are based on a stunted, under-developed form of Meccano approach which ignores much of value and interest not merely in the academic text books, but even in the manufacturers' catalogues.

The responsibility for this simultaneous neglect of the best fruits of both industry and university must, in the writer's view, be laid primarily at the feet of the academic fraternity; for where else should one look for the massive intellectual effort which is necessary to digest the vast bulk of factual data, unbiased by vested commercial interest, and to distil from it a central core of knowledge in a form usable in the pressurised surroundings of industry? At the undergraduate teaching level, the nuts and bolts of hardware find little space, whilst fundamental theory is truncated or fragmented, with scant connection with the realities of industry. At postgraduate research level, in spite of a welcome increase in recent years, the total effort is lamentably small; moreover, inevitably if understandably attention tends to be focused on the microscopic fundamentals of a few specific mechanisms rather than on a macroscopic approach aimed at synthesising existing knowledge into a form more relevant to the practical world of industry.

Over the course of the last century, industry has generated a host of different solid/liquid separation techniques, such as gravity sedimentation, flotation, centrifugal separation and filtration. The stimulus of commercial competition, combined with man's innate inventiveness, has evolved a host of alternative devices utilising any given separating principle, which may be used either alone or in various combinations. To compound the confusion, there is constant growth in the variety of pretreatment methods whereby the separation characteristics of a given solid/liquid mixture may be drastically modified, including the addition of chemical reagents, the use of heat, and the influence of radiation. The resultant range of possible choices facing the industrial technologist is alarmingly immense and totally unwieldy, reducing the optimisation of equipment for a particular duty almost to a matter of chance rather than of rational deduction.

Simultaneously, and with accelerating speed, there is growing up a body of fundamental knowledge and conjecture, sometimes in close association with industrial equipment and conditions, more often in relative or total isolation. Just how great the gap can be is perhaps demonstrated by a comparison of two recent books, the one (1) "The Scientific Basis of Filtration", being deliberately academic in its focus, whilst the other (2), "Solid/Liquid Separation Equipment Scale-up", is equally deliberately industrial; the material common to both, even allowing for the intentional differences in emphasis, is strikingly little.

Sadly, the early promise that theoretical relationships would find a ready and practical use in industry has been only partly fulfilled. In 1938, referring to cake filtration,

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(1) "The Scientific Basis of Filtration", ed. K.J. Ives, Noordhoff, Leyden, 1975.

(2) "Solid/Liquid Separation Equipment Scale-up", ed. D.B. Purchas. Uplands Press Ltd., 1 Katherine St., Croydon, Surrey. 1977.

P. C. Carman (3), complained that "design is still carried out by rule-of-thumb methods which ignore theoretically-based scales"; almost simultaneously, two American research workers (4), held out hope of better times, arguing that "the simplicity of calculations using the new Ruth equations should lead to their universal use by chemical engineers". Something obviously went badly wrong with this prediction, since as recently as 1970 we find Tiller, (5), almost repeating Carman"s words: "It is incredible that the rule of thumb applies in the design of cake filtration units rather than the rational analysis that goes into other process equipment".

The cause of this inertia (which was not in fact as total as these quotations imply) is neither simple nor single, but can be related to many interacting factors. One is the predictable increase in complexity of the relationships which were evolved as the limitations of Ruth's equations came to be better understood; as the academic strives to refine further the formulae proposed in recent years by workers such as Tiller, (6) and Shirato, (7), the results are likely to appear even less relevant to the practicalities of industry unless a major effort is made to facilitate their interpretation and use. Nor was it an encouragement to the industrial technologist a few years ago to be told, (8) that even his academic peers had until then erred in the dimensional units they had ascribed to the specific resistance to filtration of a filter cake, which should be in say m/kg and not the traditional s^2/gm.

A similar story of the shortfall in the development of theory to a point of reliable practical application in a convenient usable form exists to a greater or lesser extent in every sector of the solid/liquid separation spectrum. Thus, in gravity separation, the attractive simplicity of the Stokes model becomes rapidly bogged down in a tangle of complexities which are resolved by varying degrees of empiricism; an ultimate example of the rejection of the theoretical model is the so-called "three foot rule" (9), which empirically over-rides the depth of the compression zone in a thickener calculated by the well known procedure of Coe and Clevenger.

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(3) Carman, P.C., Trans.Inst.Chem.Eng.,16, 168-188, 1938.

(4) McMillan, E.L. & Webber, H.A., Ind.Eng.Chem.,30(6), 708-716, 1938.

(5) Tiller, F.M., Filtrn. & Sepn., 7(4), 430-433, 1970.

(6) Tiller, F.M., Chapter 14, ref. 1.

(7) Shirato, M. & Aragaki, T., Filtrn. & Sepn., 9(3), 290-297, 1972.

(8) Tebbutt, T.H.Y., J.Inst.Wat.Poln.Control,6,1970.

(9) Fitch, E.B., Chapter 4, ref.2.

The obvious similarity between gravity settling and centrifugal sedimentation is the basis of the "Sigma theory" concept, whereby a centrifuge can be characterised in terms of an "equivalent" settling area (10). The Stokes model is also the starting point of theoretical relationships for the hydrocyclone (11). But, as with the gravity separator itself, practical application of the theories evolved for both sedimenting centrifuges and hydrocyclones demands a judicious infusion of empiricism. And even greater degrees of empirical "adjustment" are necessary to allow data obtained experimentally with one type of gravitational separator to be applied to another, in spite of their evident close relationship.

To both academic and industrial technologist alike, the ideal would be to be able to characterise a solid/liquid mixture in terms of a number of fundamental properties which could then be used to calculate the necessary size of any type of separator by means of suitable theoretical relationships, just as a heat exchanger can be designed from knowledge of the density, viscosity, thermal conductivity and enthalpy of the fluids flowing. Unfortunately, with solid/liquid separation, such a fundamental approach is possible only very rarely, with the simplest examples of gravitational or centrifugal sedimentation.

The practical reality is that sizing is based on performance data, either taken from experience with a similar application, or obtained by conducting small scale or bench scale tests. Furthermore, the empirical data thus obtained are generally highly specific to the type of separator, so that separate tests are likely to be required for each type of device under consideration. Nor is that the end to the complication, since clearly the validity of the data obtained from any test programme are ultimately totally dependent on the reliability of the sample of slurry used in the tests; the difficulty of obtaining a suitable sample cannot be over-emphasised, yet is all too often overlooked. Moreover, even if the sample as taken is truly representative, its properties may be drastically altered before the tests are executed, due to factors such as ageing, changes in temperature, vibration during transit, etc: hence, serious errors may be introduced as a result of comparing data from tests conducted at different times and in different places, such as may underlie competitive quotations from several potential suppliers.

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(10) Records, F.A. Chapter 6, ref. 2.

(11) Trawinski, H., Chapter 7, ref. 2.

The research need; a two-pronged attack

The gap between industrial realities and the ideal is thus seen to be vast. Our understanding of the fundamental mechanisms underlying the various separating techniques will clearly grow as research continues, until ultimately the corpus of knowledge may be such that the gap has vanished; yet even the most optimistic of us would hardly imagine this Utopia to be achievable for many years, probably not even within the life time of the youngest person present.

A mere increase in research effort, highly desirable though this is, is not enough if this follows established lines and is concentrated in isolated pockets on the micro scale. Such pockets, concerned with exploring the fundamental mechanisms of individual separation techniques, are obviously vital and should be given all possible support. In parallel with this grass-roots attack, however, there is need to mount a significant effort in an area which is almost totally neglected; this is on the macro scale, conceived for the immediate practical benefit of industry, and aimed at welding together the existing mass of fundamental knowledge, empirical experience and equipment-based data into one integrated, USABLE whole.

The macro approach can be envisaged on two levels, the submacro which draws together a few related techniques such as the gravitational trio discussed earlier, and the supermacro which ultimately straddles the entire solid/liquid separation spectrum. Both to illustrate this more clearly, and hopefully to act as a stimulus to others, an example of both the submacro and supermacro approach will be outlined.

Submacro example: cake filtration

Although the same basic cake filtration mechanism underlies the functioning of many different types of filter, such as continuous vacuum filters, pressure leaf filters, and (often) filter presses, there is in practice no common experimental procedure to generate data for equipment sizing, and often little if any use made of even the simpler theoretical relationships; it is this neglect which provoked the remarks by both Carman and Tiller cited above. Yet, as the writer first pointed out some years ago (12), the relatively standardised procedures used for continuous vacuum filters can be easily adapted to generate data for use in making initial budget estimates of almost all types of cake filter.

Included in these "Proposals for unifying cake filtration

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(11) Trawinski, H. Chapter 7, ref.2.

(12) Purchas, D.B., Filtrn.& Sepn., 9(2),161-171, 1972

tests", (13) is the suggestion that the filtration characteristics of a slurry should be expressed as the Standard Cake Formation Time, T_f, which is the time to form a 1 cm. cake with a pressure differential of 1 atmosphere, rather than as the more fundamental specific resistance to filtration; the latter, formerly typically expressed as say $1 \times 10^9 s^2/g$, would now more correctly be 0.981×10^{13} m/kg.

The justification for this suggestion is two fold. Firstly, the units adopted are believed to be more expressive to the ordinary technologist - just as is a pressure expressed as say 2 atmospheres rather than as 2.023×10^5 Pa. Second, by making no more than the simplifying assumptions frequently used in cake filtration (notably that the medium resistance is negligible), a series of extremely simple expressions can be developed to estimate the size of continuous or batch filters to handle 1 cu.m. of cake per hour when operating at any pressure or cake thickness:

continuous filters: $A = (T_f/S_1) \times 1.67$ sq.m.

batch filters: $A = (T_f + T_D) \times 1.67$ sq.m.

pressure correction: multiply T_f in above equations by K_p where $K_p = (P_1/P_2)^{1-s}$

cake thickness correction: multiply T_f in above equations by K_C where $K_C = (C_2/C_1)^{1-s}$

where

P_1, P_2 = pressure differential, atmospheres

C_1, C_2 = cake thickness, cm.

S_1 = fraction of cycle available for cake formation.

T_D = part of cycle for operations other than cake formation, minutes.

s = cake compressibility factor

Measurement of the value of the compressibility factor, s, is thought to be potentially of major importance; a simplified method for doing this is included in the proposals (13).

For incompressible cakes, where s approximates to zero, such as with many inorganic precipitates, the proposed sizing procedure is not only simple but is no less accurate than the use of the more traditional forms of cake filtration equation.

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(13) Purchas, D.B., Chapter 13, ref.2.

In both cases, it is equally necessary to introduce an empirical scale-up factor, such as increasing the estimated area by a factor of 1.25 as is common practice with vacuum filters; the Standard Cake Formation Time procedure has the advantage that it facilitates a more rational approach with pressure leaf filters, by replacing an ad hoc scale-up factor with a reasoned analysis of how commercial filters of various fixed sizes are likely to match up to operating conditions (13), (14).

A positive value of s may serve either of two purposes, the obvious one being for use in applying the above equations. The second purpose is as a criterion to decide on the viability of either a consolidation phase in a filter press, or the use of a variable volume filter such as a membrane press, both of which depend upon the ability of a cake to compress. Tentatively, it is suggested that a value of $s <$ say 0.2 would rule out either consolidation in a filter press or the application of a variable volume filter, while above this limit additional further tests specific to these forms of solid/liquid separation are merited.

Super-macro example: a preliminary experimental selection programme.

The following screening procedure (15), (16), was evolved in the course of welding together the large number of contributions which form the substance of a recently published book which seeks to provide detailed and precise instructions on how to conduct and interpret small scale tests specific to each of the major types of solid/liquid separation device. It comprises a four-stage programme, which may be briefly summarised as follows:

1. Specification of the duty in terms of the code detailed in Figure 1. Thus, a medium scale batch operated system, where the objective is to recover the solids after washing, is coded as bdh.
2. Coding of the settling characteristics of the slurry, by observing the rate of settlement in a 1 litre cylinder, and describing the results by application of Figure 2. Thus BEG would indicate a slurry with a medium settling rate, giving a supernatent layer of good clarity, and a medium sludge layer.
3. Coding of the filtration characteristics of the slurry, using either a vacuum leaf or a Buchner funnel, and describing the results by application of Figure 3. For

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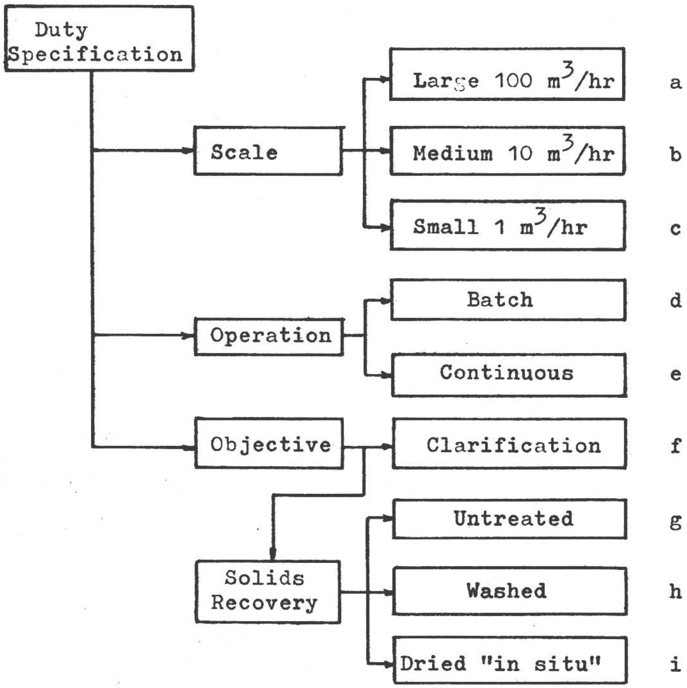
(14) Purchas, D.B., Process Engineering, Sept.1977, pp.72-75
(15) Purchas, D.B., The Chemical Engineer, No.328,47-49,1978
(16) Purchas, D.B., Chapter 1, ref.2.

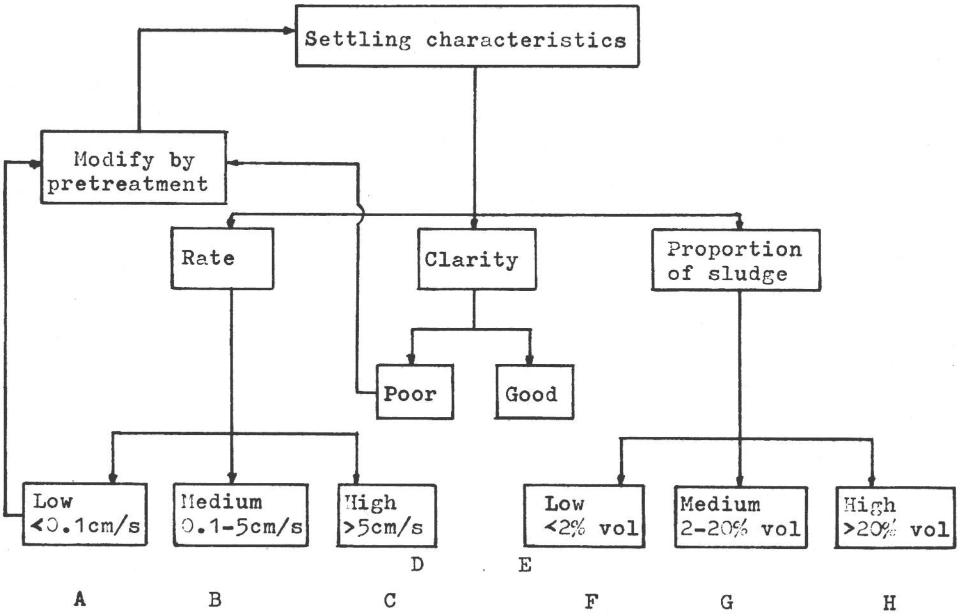
example, K indicates a medium cake growth rate; combining this with the settling characteristics (e.g. BEG from above) gives a total description of the separating characteristics of the slurry (e.g. BEGK).

4. Initial selection of equipment type, by comparing the coded duty and the coded slurry characteristics with the equipment requirements as listed in Table 1. Potential types are first identified from the duty specification alone, each type corresponding to a group of three letters (one taken from each horizontal line in the third column of Table 1). The resultant list is then shortened (if possible) by eliminating items not matching the slurry characteristics. This procedure is illustrated, for the duty and slurry specified above, in Table 2.



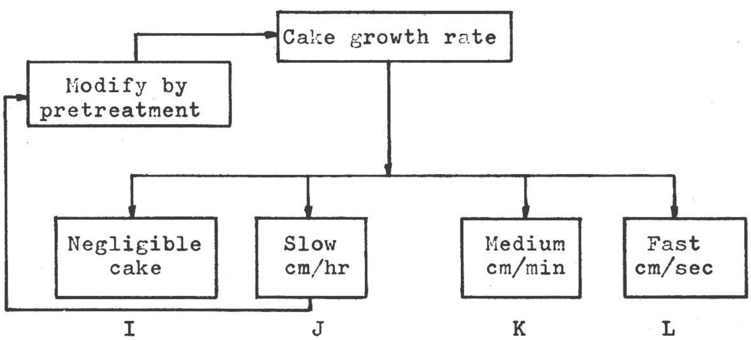
Coding the problem specification.

FIGURE 1.



Coding the settling characteristics of a slurry.

FIGURE 2.



Coding the filtration characteristics of a slurry

FIGURE 3.

TABLE 1.

Classification of equipment according to suitability for duty and slurry separation characteristics

Type of equipment	Suitable for duty specification	Required slurry separation characteristics: Slurry settling characteristics	Required slurry separation characteristics: Slurry filtering characteristics
gravity separation	a, b or c d or e f, g or h	B or C E F or G	
flotation	a or b e f or g	A D or E F	
sedimenting centrifuges			
tubular bowl	b or c d f (or g)	A or B D or E F	
skimmer pipe	a d f or g	B D or E F, G or H	
disc	a, b or c d or e f or g	A or B D or E F or G	
scroll	(a), b or c e f, g (h or i)	B or C E (or D) F or G	
hydrocyclones	a or b e f, g or h	B or C D or E F, G or H	
deep bed filters	a or b e f	A D F	I
cartridges	b or c d f	A or B D or E F	
batch filters			
pressure vessel with vertical elements	a, b or c d f, g, h or i	A or B D or E F or G	I or J
pressure vessel with horizontal elements	b or c d g or h	A or B D or E F or G	J or K

TABLE 1 (continued)

Type of equipment	Suitable for duty specification	Required slurry separation characteristics Slurry settling character-istics	Slurry filtering character-istics
filter presses	a, b or c d f, g, h or i	A (or B) D or E F, G or H	I or J
variable volume filters	a, b or c d or e g (or h)	A (or B) D or E G or H	J or K
continuous filters			
bottom-fed drum or belt-drum	a, b or c e f, g, h or i	A or B D or E F, G or H	I, J or K
top-fed drum	a, b or c e g, i (or h)	C E G or H	L
disc	a, b or c e g	A or B D or E G or H	J or K
horizontal belt, pan or table	a, b or c d or e g or h	A, B or C D or E F, G or H	J, K or L
filtering centrifuges			
peeler	a, b or c d g or h	A, B or C D or E G or H	K or L
pusher	a or b e g or h	B or C E G or H	K or L
pendulum	b or c d g or h	A, B or C D or E G or H	J, K or L
oscillating and tumbling	a e g	C E H	L
worm screen	a e g	C E H	K or L

TABLE 2.

Example of preliminary selection procedure

Duty specification: bdh   Slurry characteristics: BEGK

First selection (duty only)		Final selection
(1)	gravity separation	-
(2)	batch filters - pressure vessel, vertical elements.	-
(3)	batch filters - pressure vessel, horizontal elements	(3)

First selection (duty only)		Final selection
(4)	batch filters - filter presses	-
(5)	continuous filters - horizontal belt, pan or table	(5)
(6)	filtering centrifuges - peeler	(6)
(7)	filtering centrifuges - pendulum	(7)

Thus, types 3, 5, 6 & 7 are selected for more thorough investigation. In practice, it may be possible to narrow the field even further at this stage, by taking account of other known factors, such as the high volatility of a liquid which would tend to rule out the use of a vacuum filter.

Conclusion

Carman's complaint of 1938, that theoretical tools are ignored in favour of the rule-of-thumb, can justifiably be broadened from cake filtration, of which he was speaking, to most other sectors of the solid/liquid separation spectrum; it is even more relevant to a systematic approach to the spectrum as a whole. Research must and should continue and increase on the micro scale, focused on individual separation processes; but, in parallel with this, there is urgent need for a macro scale attack, conceived for the immediate practical benefit of industry, and aimed at welding together the existing mass of fundamental knowledge, empirical experience and equipment-based data into one integrated usable whole. The macro examples outlined perhaps give a hint of what could be achieved, but certainly by their incompleteness highlight how much there is to be accomplished.

THEORETICAL APPROACH OF FILTRATION, WASHING AND DELIQUORING OF FILTER CAKES. A SUMMARY

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1. INTRODUCTION

Filtration in the process industries has the function of the separation of two phases by mechanical means. In cake filtration, which will be considered in this paper, the particles are separated from the liquor by a porous surface e.g. filter cloth. During the process a filter cake is built and the separation goes on by the thin cake itself.
The process engineer, who is in charge of choice, lay out or optimal functioning of a given filtration system, has to be able to describe this system by means of mathematical formalism in a quantitative way. By following such an approach, it is possible to estimate and determine the impact of the final operating parameters. The objectives of the separation step are multiple and range from recuperating the liquor or the solid, washing the filter cake for purifying the cake or recuperate valuable cake liquor, deliquoring the cake in order to obtain a suitable cake or to recuperate the maximum of valuable liquor. According to the objectives, a given equipment is predestinated for solving the filtration problem.
A mathematical treatment consists of relating the properties of a filter cake, e.g. porosity, internal flow rate through the cake, internal hydraulic pressure distribution with the operating parameters, say flow rate and applied pressures. Once the properties of the filtration system are quantified in terms of specific resistance, the dependency of pressure - compressible or incompressible -, the final lay out conditions can be retained. In case, where intensive washing of the filter cake is required, an analysis of washing operation is evident, so that the step can be identified and optimised. The scope of the paper is to summarise the basic theoretical information which enables a fair description for the process engineer of a given system. The necessity of laboratory experiments is illustrated by an example and is discussed.