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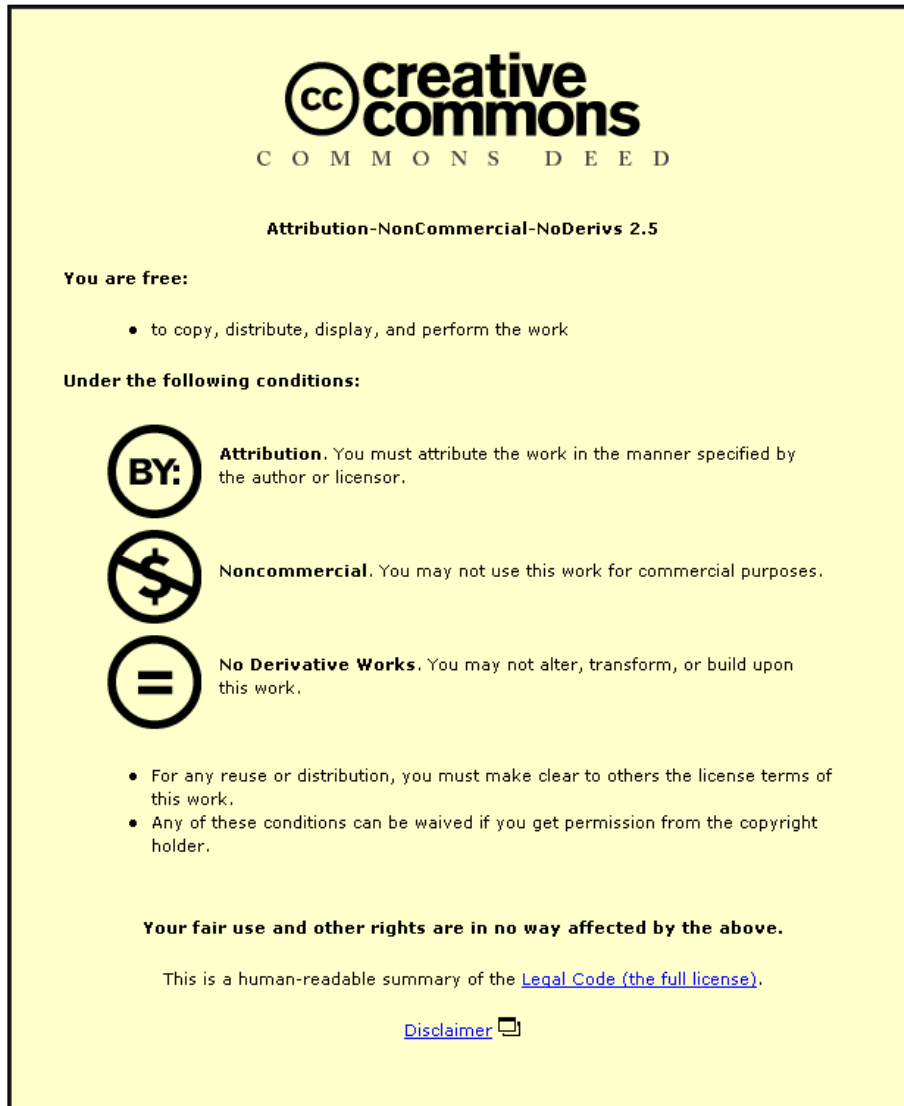
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
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## EQUIPMENT SELECTION AND PROCESS DESIGN FOR SOLID/LIQUID SEPARATION

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### ABSTRACT

This paper presents a survey of the methods of equipment selection and process design for solid/liquid separation. It is shown how a combination of automated analysis, laboratory scale test work and computer aided calculations provide the most reliable results. Current best practice is highlighted, both in terms of the computer software available (e.g. Filter Design Software) and the advantages offered by automated filter apparatus for data generation. Worked examples and example data are presented to show the capability of the overall process.

### INTRODUCTION

Many of the stages involved in the choice of filtration equipment require the use of experimentation, mainly because of the difficulties involved in routinely determining the behaviour of solid/liquid mixtures from first principles. For instance, experiments provide a basis for improved selection and scale-up, which ultimately facilitates more accurate simulation and hence more reliable equipment specification. Basic liquid filtration data can be obtained in laboratories with relatively elementary equipment, an example being the single leaf filter operating at either constant under- or over- pressure. In some cases it is possible to collect data for sequential operations such as those constituting a filter cycle, though performing these experiments manually can introduce significant errors unless great care is taken. The need to manually perform tests and adjust operational parameters to maintain chosen experimental conditions are variables that, in conjunction with variations in data analysis, can lead to:

- Extensive use of 'rules-of-thumb'
- Inappropriate sizing of filters
- Required production rates not being achieved
- Unforeseen difficulties in filter cycle operations.

The introduction of more sophisticated filtration apparatus would clearly facilitate both improved test methodologies and more detailed measurements. These raised levels of sophistication introduce new research opportunities, allow more consistent and accurate data to be obtained and provide an impetus for accompanying developments in computer software. A methodology which shows how equipment selection, scale-up and simulation are integrated with experiments and data analysis is represented by Figure 1. Whilst it is evident that filter manufacturers could also be consulted at various stages in the process, pilot-scale work could be included and 'years of experience' are invaluable, the opportunities for improved knowledge and understanding for the end-user that can be derived from the features of Figure 1 are substantial.

This paper details developments in equipment for the automated testing and monitoring of cake filtration and the filter cycle, and shows how the level of sophistication can be varied according to requirements. The integration of reliably obtained test data with interactive computer software is used to illustrate a robust approach to equipment selection. The paper also shows how such information can subsequently be used in conjunction with process modelling to simulate detailed filter cycle operations on cake filters. The combined use of state-of-the-art test apparatus and software such as Filter Design Software™ (FDS, 2005) is already a reality in some industry sectors and has the potential for widespread application within most of the process and related industries.

## EQUIPMENT SELECTION

To perform equipment selection according to Figure 1, a number of different schemes have been proposed. Although some literature appeared as early as the 1920's (e.g. Sperry (1924)), the few publications before the 1960's primarily concerned details of filters, their qualitative performance and/or general guidance towards their use (see, for example, Grace (1951) and Smith (1955)). Since 1964, however, the scope and number of selection procedures has widened and followed a number of diverse, and sometimes confusing, routes. The information available may be categorised into five groups:

- a) *General information*: Hicks and Hillgard (1970), Maloney (1972) and Alt (1975).
- b) *Non-ranked table*: Equipment is placed in a list relative to some characterising parameter or performance indicator such as feed concentration, particle size in the feed or standard cake formation time. Tables have been produced by Flood *et al.* (1966), Davies (1970), Purchas (1970; 1972a; 1978; 1981), Hawkes (1970), Emmett and Silverblatt (1975), Day (1974), Dahlstrom (1978), Gaudfrin and Sabatier (1978), Trawinski (1980), and Purchas and Wakeman (1986).
- c) *Ranked table*: Equipment performance is rated by one or more numerical indices to produce ranked lists. Indices are typically valued between 0 and 9 (best) and related to operational parameters such as solid product dryness, crystal breakage etc. Contributions have been made by Davies (1965), Purchas (1972b), Fitch (1974, 1977), Moos and Dugger (1979), Komline (1980) and Ernst *et al.* (1991).
- d) *Logic diagram*: A decision tree guides a user through a series of yes/no choices towards a potentially suitable generic class of separation equipment. Logic diagrams have been produced by Davies (1965), Tiller (1974) and Pierson (1990).
- e) *Expert system*: Rule-based computer programs select and rank potentially suitable separation equipment. Expert system approaches have been independently developed by Korhonen *et al.* (1989), Ernst *et al.* (1991), Garg *et al.* (1991) and Wakeman and Tarleton (1991).

The charts, tables and general information contained in categories (a)-(d) can be used as guides toward an initial selection of solid/liquid separation equipment. The better contributions consider a wider variety of possible eventualities, and indicate clearly where decisions must be made. The charts and tables have generally been devised by experts to be fairly comprehensive, and are of greatest value to the solid/liquid separation expert. They, unfortunately, also illustrate the near-impossibility of combining comprehensive descriptions with usability. Without 'expert' guidance it is extremely difficult for an end-user to correlate information and decide which equipment is more suitable for any particular application. Also, having identified potentially suitable equipment, it can be equally as difficult to check such basic requirements as separator area and likely throughput rate.

It is clear that there has previously been no accepted standard approach to solid/liquid equipment selection and the development of computer software is an ideal way to tackle the issue. Whilst rule-based expert systems appeared to provide the optimum solution at first, it became apparent to some researchers that inherent restrictions would prevent their widespread application. With current levels of knowledge, it is necessary for software to be interactive and designed in a way to be integrated with a basic experimental programme. Such an approach could be eliminated if measurable microscopic properties of suspensions and filter cakes could be related to their bulk behaviour. The need for empirical corrections and 'averaging' factors would then be eliminated and all macroscopic properties could be predicted from the individual properties of the particles and fluid. Although engineers and scientists have pursued this goal for many years, the present reality necessitates some reliance on experimental data. Thus, interactive computer software, based on a dual expert system/experiment approach, is required.

Such software has previously been developed to commercial standards (Wakeman and Tarleton (1991)) and further adapted and expanded for incorporation within FDS (Tarleton and Wakeman

(2003)). The favoured method, and the one in-built within FDS, is to use a limited amount of data about the process duty (scale of operation, batch or continuous, principal objective), preliminary knowledge of separability of the feed stream (experimental data from a simple laboratory scale leaf filter and/or jar sedimentation) and a form of inference mechanism (selection chart or table, typically relating to 70+ types of equipment). This combination allows the identification of a range of equipment that could be expected to carry out the required separation. A longer list is produced if experimental data are not available. By incorporating the 'ranked tables' described in (c) above it is possible to produce a numerically ranked equipment list. The final shortlist contains those items which are worthy of further evaluation through pilot testing and/or computer simulation. Full details are available in Tarleton and Wakeman (2006).

### Example of Use

For batch plants where several products are manufactured in small to medium quantities the same piece of equipment may be required to perform several different separations. In such circumstances a good deal of heuristic information and detailed knowledge of a wide variety of separators is needed in order to identify a shortlist of equipment.

Consider a plant which is required to process five separate feeds in batches at rates equivalent to  $\sim 15 \text{ m}^3 \text{ h}^{-1}$ . At the current stage of process specification it is not clear whether the prime objective for the separation of two of the feeds is solids dewatering or washing. Sedimentation and filtration tests have been performed on small samples of feed and analysed using FDS to give the data in Table 1. Determine if the separation of all five feeds could be achieved effectively using a single separator.

### Solution

The data in Table 1 indicate that the separation characteristics of each feed are quite different. By repeated use of the automated selection procedures in FDS, the information in Table 2 can be produced.

The numbers listed under the sub-headings 'D' and 'W' indicate the relative performance index of the equipment as a solids dewatering or cake washing device, respectively. Inspection shows that none of the separators identified are capable of processing all five feeds in an effective manner, although the pressure Nutsche filter and basket pendulum centrifuge are suited to processing four of the five feeds. Should only the un-flocculated feeds need to be processed, then the pressure Nutsche is a good choice for further investigations. Whilst the diaphragm filter press has high ratings for feeds #2 – #4, difficulties are identified with the processing of feeds #1 and #5 due respectively to a small proportion of sludge (which infers a low cake volume and long cycle times) and excessive particle settling in the chambers of the press. The basket pendulum centrifuge is also eliminated for feed #1 due to the inadequate proportion of sludge. The ultimate choice of separator(s) may ultimately depend upon either modification to the separation characteristics of, for instance, feeds #1 or #5 and/or consideration of additional factors.

## EXPERIMENTAL EQUIPMENT

The need to generate experimental data to aid equipment selection, and as detailed later to expedite equipment simulation, has led to the development of more sophisticated filtration apparatus, improved test methodologies and more detailed measurements; examples include Fathi-Najafi (1994), Green *et al.* (1998), Jämsä-Jounela and Oja (2000), Teoh *et al.* (2001), Usher *et al.* (2001), Johansson and Theliander (2002), Townsend (2002), Anderson *et al.* (2004) and Cambridge Reactor Design (2010).

In the case of the authors work, manual operation has been replaced by a mechatronics philosophy that combines electronics, computer technology and automatic control to facilitate experiments over any chosen pressure/flow regime. Figures 2 and 3 show examples of state-of-

the-art, laboratory scale experimental apparatus capable of automated data acquisition during sequential filtration, displacement washing and gas deliquoring phases of a filter cycle; the level of hardware and software sophistication can be varied according to requirements. For details of development see Tarleton and Hancock (1996, 1997), Tarleton and Willmer (1997), Tarleton (1998, 1999a, 1999b), Tarleton and Hadley (2003) and Tarleton and Wakeman (2006); the latter also provides detail of advanced equipment for determinations of compression deliquoring.

The basic hardware comprises of a stainless steel (s/s) deadend Nutsche filter (area 80 → 500 cm<sup>2</sup>) and a s/s feed suspension storage vessel connected by s/s piping and computer controlled electro-pneumatic valving; the storage vessel incorporates a stirrer. A heater/cooler system regulates the temperature of the filter cell and storage vessel by continuously passing a fluid through their surrounding jackets to facilitate operation over the range 10 → 70°C. Various transducers attached to the apparatus allow pressures and other measured parameters to be recorded and/or controlled by the interfaced computer and dedicated software.

The pressures required to progress filtrations are provided by a compressor and an electronic pressure regulator over the range 10 → 1000 kPa. The regulator is adjusted by the computer and the filtrate flow rate is semi-continuously transmitted to the computer via successive timed readings of mass from the electronic balance. By monitoring the flow rate in such a manner, use of a suitable software control algorithm allows either constant pressure, stepped pressure, constant rate or variable pressure/variable rate filtration to be performed without changing the suspension properties through inappropriate pumping operations. This approach overcomes the long-standing difficulties of performing variable pressure filtrations at the small scale. The rate and magnitude of the pressure adjustments is dependent on the nature of the feed, the compressibility of the filter cake and the desired process conditions.

In order to monitor (in real time) the rate of cake growth, filter cake structure (during filtration), solute concentration profiles in the cake (during any washing phase) and/or cake saturation profiles (during any deliquoring phase) a series of small electrodes can be fitted internally within the filter cell. The electrodes which may protrude a short distance into the cell are arranged in single vertical planes or, if maximum data are required, in sequences of horizontal rings. Signals to electrode pairs are switched by the attached computer via electronic circuitry to facilitate measurements. Alternatively, micro-pressure transducers can be used in place of electrodes to determine cake structure and these are capable of delivering measurements of liquid pressure within 0.3 mm of the filter medium. With seven transducers within ~3 mm of the filter medium the initial stages of cake formation, i.e. the most important, can be well monitored.

The use of computer control allows sequential filter cycle data to be acquired in a repeatable and reliable manner with a minimum of operator interference. By defining the desired cycle phases through a software algorithm, a cake formation phase can be directly followed by the chosen combination of washing and deliquoring. The real time measurement of experimental parameters also allows continuous display of results and the use of on-line analysis techniques as an experiment proceeds.

### Example Data

Whilst many data could be shown, Figure 4 provides a typical illustration of those measurable together with their reproducibility. Measured volume of filtrate ( $V$ ) vs. time ( $t$ ) data are reproducible and for the four experiments shown the specific cake resistance, filter medium resistance and cake porosity were respectively determined as  $1.46 \times 10^{11} \pm 2 \times 10^9 \text{ m kg}^{-1}$ ,  $3.7 \times 10^{11} \pm 1 \times 10^{10} \text{ m}^{-1}$  and  $0.67 \pm 0.005$ . There is usually slightly more, but still acceptable, variation in the liquid pressures measured with the micro-pressure transducers. The data can be interpreted as follows. At the start of filtration ( $t = 0 \text{ s}$ ) a suspension is in its original homogeneously mixed state and liquid pressures are equal to the applied filtration pressure. For a 400 kPa filtration pressure, after 10 s a cake of just over 2 mm had formed. At this stage many of the particles comprising the cake are (at least) in point contact to raise the solids compressive pressure and induce a corresponding reduction in liquid pressure. Near to the filter medium the solids pressure is at its greatest (as is the local cake resistance) whilst further away from the medium the solids pressure is lower and at

the ultimate cake height equal to zero. As time progresses in the filtration, cake thickness increases and the moderately compressible talc cake becomes more compact due to the continual flow of liquid through the cake interstices and the increasing weight of particles above those already constituting the cake. Towards the end of cake formation ( $t = 125$  s) the cake thickness approaches 9.3 mm as evidenced by the falling liquid pressure at that height.

## DATA ANALYSIS

It is probably fair to say that a significant proportion of previous filtration research and data acquisition has been blighted by experimental difficulties and/or the skill (or otherwise) with which experiments are performed. Whilst use of the experimental apparatus described will undoubtedly help to improve the situation, it is equally necessary to provide consistent and robust data analysis procedures to ensure that the correct data are acquired for inputs to equipment selection and simulation procedures. Computer software, such as FDS, can be used to correctly analyse leaf filtration, jar sedimentation and piston press experiments to give both basic values for equipment selection and scale-up coefficients for equipment simulation (see also Figure 1). In such a way, common errors are eliminated.

Constant pressure tests are most frequently used to obtain laboratory data that characterise filter performance and scale-up as experimental arrangements are relatively straightforward. It is conventional practice to record cumulative time and volume of filtrate and convert these into a 'Characteristic Plot' of time/volume vs. volume. Ideally a straight line is produced from which cake resistance and filter medium resistance can be calculated. In reality, however, deviations from this ideal are frequently observed as shown in Figure 5. Non-linearities close to the start of filtration are normally due to interactions between the filter medium and the initial layers of particles forming the cake and/or poor drainage characteristics of the test filter; the latter can render experiments worthless. Non-linearities toward the end of filtration can occur if:

- the filtration is carried out in a filter with a fixed volume chamber, then when the chamber is full of cake the filtrate volume collected in any time interval is reduced
- a cake is formed and the feed slurry is completely used, then the applied pressure difference serves to deliquor the cake and again the filtrate flow rate is considerably reduced
- settling of the solids has occurred during the test, then the data sequence tends to assume a horizontal plateau as permeation (rather than filtration) proceeds.

Any of the above deviations from linearity can lead to significant errors when calculating cake and filter medium resistances as well as final cake moisture – errors are thus magnified when sequences of data obtained at different constant pressures are used to calculate the scale-up coefficients required for simulation. To promote better data analysis and more reliable scale-up it is recommended that:

- Careful observations are made during an experiment, particularly toward the end so that the final cake condition is known
- Suitable corrections are applied to account for the loss of liquid from the final cake due to any deliquoring
- The linear region of the time/volume vs. volume is chosen carefully.

In computer software like FDS, moveable line cursors are used to identify a linear or transition region on the Characteristic Plot and these are initially positioned by the software via numerical inference techniques. However, the user has facility to interact with the software and move the cursors as appropriate in order to overcome their potential misplacement due to excessive data scatter. In this way the analysis can be amended as many times as required and optimised.

Even with well conducted tests some of the necessary input data can be missing, yet the best possible analysis must still be done with the available information. Computer software such as FDS deals with this situation in two ways. Firstly, when the input data are entered they are

checked as far as is possible and if incorrect data are suspected then a warning is issued; in many cases a range of acceptable values for the data is also displayed as a guide to the user. Secondly, the calculation sequences are hierarchical as, depending on which data are missing, a sequence of assumptions are made in order to carry out the calculations.

## EQUIPMENT SIMULATION

With selection performed to produce a ranked list of potential suitable equipment, and data analysis performed to generate scale-up coefficients which quantify the variation of cake resistance and cake structure with pressure, the simulation of filtration equipment can be undertaken (see Figure 1). Although detailed equations and calculations will not be shown, the interested reader is directed to Tarleton and Wakeman (2006), it is clear that the use of computer simulations of a filter cycle involving filtration, deliquoring and/or washing can bring benefits both in terms of knowledge gained and money saved provided that appropriate levels of user interaction and ease of information transfer are maintained.

Early efforts to model the filter cycle, for example Carman (1938), were followed in the years up to 1990 by several attempts to produce charts for selecting solid/liquid separation equipment (as detailed above). During the same period attempts were also made to model aspects of the filter cycle on devices such as rotary vacuum filters and centrifuges (see, for example, Nelson and Dahlstrom (1957), Kelsey (1965), Rushton (1978), Wakeman (1979, 1981), Wakeman and Mulhaupt (1985), Shirato *et al.* (1987), Yelshin *et al.* (1989) and Wakeman and Wei (1995)). In more recent years efforts have led to further simulations of rotary vacuum filters (Stahl and Nicolaou (1990), and Nicolaou (2003)) as well as investigations of the belt press filter (Kobayashi *et al.* (1993)) and the rotary disc filter (Nyström (1993)). Perhaps the greatest progress was made by the introduction of FDS in 2003 and other rival software; details of the development of FDS can be found in Wakeman and Tarleton (1990, 1994) and Tarleton and Wakeman (1994, 2006).

Software like FDS is typically capable of simulating 20+ types of vacuum and pressure filters to give filter area and performance indicators for filter cycles involving cake formation at both fixed and variable pressure/flow conditions, compression and gas deliquoring as well as displacement washing. Typical vacuum filters are Nutsche, multi-element leaf, belt, drum, disc, table and tilting pan filters, whilst typical pressure filters include single and multi-element leaf filters, diaphragm and filter presses as well as the tube press. Again, a combined experimental (evaluation of scale-up coefficients) and theory is required to give the best results.

### Example of Use

A pressure driven Nutsche filter is to be used to separate batches of a crystalline pharmaceutical product from a propanol based suspension. Variations in upstream formulation mean that crystallisation of the  $\beta$ -form, which is more difficult to filter, can occur in place of the  $\alpha$ -form. In each batch, 50 kg of solids are present at a concentration of 6% v/v and it is envisaged that cake formation will occur to a maximum depth of 50 mm. In order to meet product specifications this new filter installation requires a sequential cycle comprising filtration, displacement washing and gas deliquoring. Preliminary tests in the laboratory suggest that the cake formed in each cycle needs to be treated with 3.5 wash ratios of pure propanol to remove unwanted solute residues after which deliquoring (with pressurised nitrogen) proceeds for 1500 s to dry the cake ready for discharge with the plough.

The cake characteristics for both the  $\alpha$  and  $\beta$  particle forms in suspension have been determined experimentally and analysed using FDS. These are shown in Table 3 along with other suggested operational parameters.

For the  $\alpha$ -form, determine the required filter area, the solid, liquid and solute throughput rates, the filter cycle time and other performance indicators. Assess the impact on the filter cycle if  $\beta$ -form crystallisation occurs.

### Solution

Repeated simulation with FDS shows that for the  $\alpha$ -form the required filter area is 2 m<sup>2</sup> for the specified 50 kg of solids per batch and 50 mm cake thickness. Each cake discharged from the Nutsche contains ~16.6 kg of propanol and (theoretically) no undesirable solutes. A total of 637 kg of propanol passes through the filter per batch, including 178 kg of wash liquid and 5.14 kg of solutes are removed with the filtrate (4.57 kg) and washings (0.57 kg). As shown in the penultimate row of Table 4, the total cycle time is 2775 s.

According to Table 4, the  $\beta$ -form produces a cake of higher compressibility as evidenced by the constitutive equations for cake resistance and solids volume fraction. If simulations are performed for the  $\beta$ -form with the 2 m<sup>2</sup> Nutsche then the results summarised in Table 4 are obtained. Due to different intrinsic properties, a cake containing 50 kg of solids exhibits a thickness of 47.4 mm rather than the 50 mm observed with the  $\alpha$ -form. The approximate fourfold increase in specific cake resistance with the  $\beta$ -form more than doubles the total cycle time and leads to a significantly wetter cake at the end of deliquoring (i.e. 28.6% compared with 24.9% for the  $\alpha$ -form). To achieve a 24.9% moisture content would require either a deliquoring time of ~4300 s at the original 200 kPa pressure or a raised deliquoring pressure of 480 kPa applied for the specified 1500 s. The implications of processing the  $\beta$ -form of particle are significant in terms of either longer cycle times and/or raised equipment specification.

It is evident that a reduced maximum cake thickness would lead to reduced filtration and deliquoring times, albeit at the expense of a larger filter area and the potential limitation of increased channelling (during washing) with excessively thin cakes. Conversely a thicker cake would lead to a smaller filter but longer processing times.

### CONCLUSIONS

Filtration equipment is rarely specified without recourse to extensive laboratory and/or pilot scale tests. The cost of such testing is high, particularly if the process is taken from initial trials performed to identify potentially suitable equipment right through to larger scale testing. The lack of a consistent approach can lead to the poor specification and sizing of filters with the result that required production rates may not always be achieved and unforeseen difficulties arise in filter cycle operations. Against such a background this paper has presented the potential benefits of a combined theoretical and experimental approach to equipment selection, scale-up and simulation. Provided the necessary simulations are available, a range of scenarios can be examined relatively quickly and comparisons between equipment types made. 'What if?' questions can be readily answered and the consequences of, for instance, variations in feed properties or processing different feed types assessed. In principle, near optimum processing conditions can also be established. A further benefit of using a range of simulations is that an unbiased assessment of separator performance can be acquired prior to approaching a manufacturer, thus reducing the risk of incorrect or non-ideal equipment selection.

Overall, the author believes that the approach presented not only allows for better equipment specification but also an opportunity to educate users in filtration technology.

### REFERENCES

Alt C., 1975, Practical problems in choosing filtration process and future developments, in *The Scientific Basis of Filtration*, Ed. K.J. Ives, pp.411-444, Noordhoff, Leyden.

Andersen N.P.R., Christensen M.L. and Keiding K., 2004, New approach to determining consolidation coefficients using cake-filtration experiments, *Powder Technology*, **142**, 98-102.

Cambridge Reactor Design, 2010, *Falcon Filtration Robot Assistant brochure*, [www.cambridgereactor.com](http://www.cambridgereactor.com)

Carman P.C., 1938, Fundamental principles of industrial filtration, *Trans IChemE*, **16**, 168-188.

Dahlstrom D.A., 1978, How to select and size filters, in *Mineral Processing Plant Design*, Eds. A.L. Mular and R.B. Bhappu, pp.578-600, AIME, New York.

Davies E., 1965, Selection of equipment for solid/liquid separations, *Trans IChemE*, **43**, 256-259.

Davies E., 1970, What is the right choice of filter or centrifuge, *Filtration and Separation*, **7**, 76-79.

Day R.W., 1974, Techniques for selecting centrifuges, *Chem. Engng.*, **81**, 98-104.

Emmett R.C. and Silverblatt C.E., 1975, When to use continuous filtration hardware, *Filtration and Separation*, **12**, 577-581.

Ernst M., Talcott R.M., Romans H.C. and Smith G.R.S., 1991, Tackle solid-liquid separation problems, *Chem. Eng. Prog.*, **87**, 22-28.

Fathi-Najafi, M., 1994, Cake filtration – A study of non-reversible compressible materials, *PhD Thesis*, Chalmers University of Technology, Göteborg, Sweden.

*Filter Design Software*, 2005, Filtration Solutions, UK. ([www.filtrationsolutions.co.uk](http://www.filtrationsolutions.co.uk)).

Fitch B., 1975, Current theory and thickener design: Part 3 – Design procedures, *Filtration and Separation*, **12**, 636-638.

Fitch B., 1977, When to use separation techniques other than filtration, *AIChE Symposium Series*, **73**(171), 104-108.

Flood J.E., Porter H.F. and Rennie F.W., 1966, Filtration practice today, *Chem. Eng.*, **73**, 163-181.

Gaudfrin G. and Sabatier E., 1978, Tentative procedure to choose a filtration equipment, *Proc. Symposium on Liquid/Solid Filtration*, pp.29-47, Soc. Belge de Filtration, Amsterdam.

Garg M.K., Douglas P.L. and Linders J.G., 1991, An expert system for identifying separation processes, *Can. J. Chem. Engng.*, **69**, 67-75.

Grace H.P., 1951, What type of filter and why, *Chem. Eng. Prog.*, **47**, 502-507.

Green M.D., Landman K.A., de Kretser R.G. and Boger D.V., 1998, Pressure filtration technique for complete characterisation of consolidating suspensions, *Ind. Eng. Chem. Res.*, **37**(10), 4152-4156.

Hawkes R.O., 1970, Optimum utilisation of equipment characteristics, *Filtration and Separation*, **7**, 311-318.

Hicks C.P. and Hillgard A., 1970, Pressure filtration or centrifugal separation - complementary or competitive, *Filtration and Separation*, **7**, 456-460.

Kelsey G.D., 1965, Some practical aspects of continuous rotary vacuum filters, *Trans IChemE*, **43**, T248-T255.

- Kobayashi Y., Ohba S. and Shimuzu K., 1993, Analysis of dewatering performance of belt press filter, *Proc. 6<sup>th</sup> World Filtration Congress*, pp. 778-781, Japanese Filtration Society, Nagoya.
- Komline T.R., 1980, Sludge dewatering equipment and performance, *AIChE Symposium Series*, **76**(197), 321-332.
- Korhonen E., Lahdenperä E. and Nyström L., 1989, Selection of equipment for solid-liquid separation by expert systems, *Proc. Filtech Conference*, pp.436-443, The Filtration Society, Karlsruhe.
- Jämsä-Jounela S.L. and Oja M., 2000, Modelling module of the intelligent control system for the variable volume pressure filter, *Filtration and Separation*, **37**(2), 39-49.
- Johansson C. and Theliander H., 2002, Measuring concentration and pressure profiles in dead-end filtration, *Proc. European Conference on Filtration and Separation*, pp.156-164, Nordic Filtration Society, Göteborg, Sweden.
- Maloney G.F., 1972, Selecting and using pressure leaf filters, *Chem. Engng.*, **79**(11), 88-94.
- Moos S.M. and Dugger R.E., 1979, Vacuum filtration: Available equipment and recent innovations, *Minerals Engineering*, **31**, 1473-1486.
- Nelson P.A. and Dahlstrom D.A., 1957, Moisture-content correlation of rotary vacuum filter cakes, *Chem. Eng. Prog.*, **53**(7), 320-327.
- Nicolaou I., 2003, An innovative computer programme for analysing filtration data and filter calculation, *Proc. Filtech Conference*, pp.191-199, Düsseldorf, Germany.
- Nyström L.H.E., 1993, Simulation of disc filter for the pulp and paper industries, *Filtration and Separation*, **30**, 554-556.
- Pierson H.G.W., 1990, The selection of solid/liquid separation equipment, in *Solid-Liquid Separation*, 3<sup>rd</sup> Edn., Ed. L. Svarovsky, pp.525-538, Butterworths, London.
- Purchas D.B., 1970, A non-guide to filter selection, *Chemical Engineer*, **237**, 79-82.
- Purchas D.B., 1972a, Guide to trouble-free plant operation, *Chem. Engng.*, **79**, 88-96.
- Purchas D.B., 1972b, Cake filter testing and sizing. A standardised procedure, *Filtration and Separation*, **9**, 161-171.
- Purchas D.B., 1978, Solid/liquid separation equipment. A preliminary experimental selection programme, *Chemical Engineer*, **328**, 47-49.
- Purchas D.B., 1981, *Solid/Liquid Separation Technology*, Filtration Specialists, UK.
- Purchas D.B. and Wakeman R.J. (Eds.), 1986, *Solid/Liquid Separation Equipment Scale-up*, 2<sup>nd</sup> Edn., Uplands Press & Filtration Specialists Ltd, London.
- Rushton A., 1978, Pressure variation effects in rotary drum filtration with incompressible cakes, *Powder Technology*, **20**, 39-46.
- Shirato M., Murase T., Iritani E., Tiller F.M. and Alciatore A.F., 1987, Filtration in the chemical process industry, in *Filtration*, Eds. M.J. Matteson and C. Orr, Marcel Dekker, New York.

- Stahl W. and Nicolaou I., 1990, Calculation of rotary vacuum plant, *Proc. 5<sup>th</sup> World Filtration Congress*, pp.37-44, Société Française de Filtration, Nice.
- Smith J.C., 1955, How to approach your separation problem, *Chem. Engng.*, **62**(6), 177-184.
- Sperry D.R., 1924, What is the most suitable filter, *Chem. Metall. Engng.*, **31**, 422-428.
- Tarleton E.S., 1998, A new approach to variable pressure cake filtration, *Minerals Engineering*, **11**(1), 53-69.
- Tarleton E.S., 1999a, Using mechatronics technology to assess pressure filtration, *Powder Technology*, **104**, 121-129.
- Tarleton E.S., 1999b, The use of electrode probes in determinations of filter cake formation and batch filter scale-up, *Minerals Engineering*, **12**(10), 1263-1274.
- Tarleton E.S. and Hadley R.C., 2003, The application of mechatronic principles in pressure filtration and its impact on filter simulation, *Filtration*, **3**(1), 40-47.
- Tarleton E.S. and Hancock D.L., 1996, The imaging of filter cakes through electrical impedance tomography, *Filtration and Separation*, **33**(6), 491-494.
- Tarleton E.S. and Hancock D.L., 1997, Using mechatronics for the interpretation and modelling of the pressure filter cycle, *Trans IChemE*, **75**(A), 298-308.
- Tarleton E.S. and Wakeman R.J., 1994, The simulation, modelling and sizing of pressure filters, *Filtration and Separation*, **31**, 393-397.
- Tarleton E.S. and Wakeman R.J., 2003, New computer software for the selection of solid/liquid separation equipment, *Proc. Filtech conference*, pp.200-207, Düsseldorf, Germany.
- Tarleton E.S. and Wakeman R.J., 2006, *Solid/Liquid Separation: Equipment Selection and Process Design*, Elsevier, Oxford.
- Tarleton E.S. and Willmer S.A., 1997, The effects of scale and process parameters in cake filtration, *Trans IChemE*, **75**(A), 497-507.
- Teoh S.K., Tan R.B.H., He D. and Tien C., 2001, A multifunction test cell for cake filtration studies, *Trans Filtration Society*, **1**(3), 81-90.
- Townsend I., 2002, Pressure filtration, Paper presented at 'Solid/Liquid Separation Plant Design' conference, 13 pages, The Filtration Society, Birmingham.
- Tiller F.M., 1974, Bench scale design of SLS systems, *Chem. Engng.*, **81**, 117-119.
- Trawinski H.F., 1980, Current solid/liquid separation technology, *Filtration and Separation*, **17**, 326-335.
- Usher S.P., de Kretser R.G. and Scales P.J., 2001, Validation of a new filtration technique for dewaterability characterisation, *AIChEJ*, **47**(7), 1561-1570.
- Wakeman R.J., 1979, The performance of filtration post-treatment processes: 1. The prediction and calculation of cake dewatering characteristics, *Filtration and Separation*, **16**, 655-660.

Wakeman R.J., 1981, The analysis of continuous countercurrent washing systems, *Filtration and Separation*, **18**, 35-41.

Wakeman R.J. and Mulhaupt B., 1985, Process design and scale-up of multi-stage washing pusher centrifuges, *Filtration and Separation*, **22**, 231-234.

Wakeman R.J. and Tarleton E.S., 1990. Modelling, simulation and process design of the filter cycle, *Filtration and Separation*, **27**, 412-419.

Wakeman R.J. and Tarleton E.S., 1991, Solid/liquid separation equipment simulation and design - an expert systems approach, *Filtration and Separation*, **28**, 268-274.

Wakeman R.J. and Tarleton E.S., 1994, A framework methodology for the simulation and sizing of diaphragm filter presses, *Minerals Engineering*, **7**, 1411-1425.

Wakeman R.J. and Wei X., 1995, Simulating the performance of tilting pan filters, *Filtration and Separation*, **32**, 979-984.

Yelshin A. and Tiller F.M., 1989, Optimising candle filters for incompressible cakes, *Filtration and Separation*, **26**, 436-437.

## TABLES AND FIGURES

Selection parameter in FDS	Feed #1	#2	#3	#4	#5*
Primary separation objective	D	D	D	D or W	D or W
<i>(Sedimentation test data)</i>					
Settling rate (cm s <sup>-1</sup> )	< 0.1	< 0.1	< 0.1	0.1-5	> 5
Clarity of supernatant	poor	poor	good	good	good
Sludge proportion (%)	< 2	> 20	> 20	2-20	2-20
<i>(Filtration test data)</i>					
Cake growth rate (cm min <sup>-1</sup> )	< 0.02	< 0.02	0.02-1	0.02-1	> 1

D ≡ dewatered cake, W ≡ washed cake; \*#5 is flocculated from #4

Table 1: Settling and filtration characteristics of five batch feeds.

Equipment identified by FDS	#1	#2	#3	#4		#5	
	D	D	D	D	W	D	W
Filter press	6	6	-	-	-	-	-
Single leaf (pressure Nutsche) filter	6	6	6	6	8	-	-
Multi-element tubular candle filter	5	-	-	-	-	-	-
Multi-element leaf (vertical element) filter	5	-	-	-	-	-	-
Multi-element leaf (horizontal element) filter	-	-	-	-	8	-	-
Diaphragm filter press	-	8	8	8	8	-	-
Multi-element leaf vacuum filter	5	-	-	5	5	-	-
Tube press	-	8*	8*	8*	4*	-	-
Basket (pendulum) centrifuge	-	9	9	9	6	9	6
Basket (peeler) centrifuge	-	-	9	9	6	9	6
Circular basin thickener	-	-	-	-	2	-	2
Screen classifier	-	-	-	-	4*	-	4*
Gravity Nutsche filter	-	-	-	4*	7*	4*	7*

D ≡ dewatering index; W ≡ washing index; \*marginally acceptable; "-" ≡ unsuitable.

Table 2: Equipment potentially suited to the processing of the five batch feeds.

Parameter	Value
<i>Septum characteristics</i>	
Filter medium resistance ( $m^{-1}$ )	$4 \times 10^{10}$
<i>Operating conditions</i>	
Filtration, washing and deliquoring pressures (kPa)	200
Solute concentration in the feed ( $kg\ m^{-3}$ )	9
<i>Particle and fluid properties</i>	
Density of filtrate and wash ( $kg\ m^{-3}$ )	802
Viscosity of filtrate and wash (Pa s)	0.0023
Surface tension of filtrate and wash ( $N\ m^{-1}$ )	0.025
Solute diffusivity ( $m^2\ s^{-1}$ )	$6 \times 10^{-10}$
<i>Particle and cake properties specific to <math>\alpha</math>-form</i>	
Density of solids ( $kg\ m^{-3}$ )	1370
Constitutive equations for filtration. $\Delta p_f$ in kPa	$\alpha_{av} = 5.6 \times 10^9 \Delta p_f^{0.2}\ m\ kg^{-1}$ $C_{av} = 0.28 \Delta p_f^{0.05}\ v/v$
<i>Particle and cake properties specific to <math>\beta</math>-form</i>	
Density of solids ( $kg\ m^{-3}$ )	1420
Constitutive equations for filtration. $\Delta p_f$ in kPa	$\alpha_{av} = 4.5 \times 10^9 \Delta p_f^{0.5}\ m\ kg^{-1}$ $C_{av} = 0.27 \Delta p_f^{0.06}\ v/v$

Table 3: Characteristic parameters for the Nutsche filter simulation.  $\Delta p_f$  is filtration pressure;  $\alpha_{av}$  is specific cake resistance;  $C_{av}$  is cake solids concentration.

Parameter	$\alpha$ -form	$\beta$ -form
<i>Filtration phase</i>		
Duration (s)	707	2363
Specific cake resistance ( $m\ kg^{-1}$ )	$1.62 \times 10^{10}$	$6.36 \times 10^{10}$
Cake solids volume fraction (v/v)	0.365	0.371
Cake thickness (mm)	50	47.4
Cake moisture content (%)	50.5	48.9
<i>Washing phase</i>		
Duration (s)	568	1959
Fractional solute recovery	1	1
<i>Deliquoring phase</i>		
Duration (s)	1500	1500
Final cake moisture content	24.9	28.6
<i>All phases</i>		
Total cycle duration (s)	2775	5822
Total volume of liquids produced ( $m^3$ )	0.773	0.736

Table 4: Comparison of filter cycle performance for two particle forms in a Nutsche filter.  $\Delta p_f = 200\ kPa$ ;  $A_f = 2\ m^2$ .

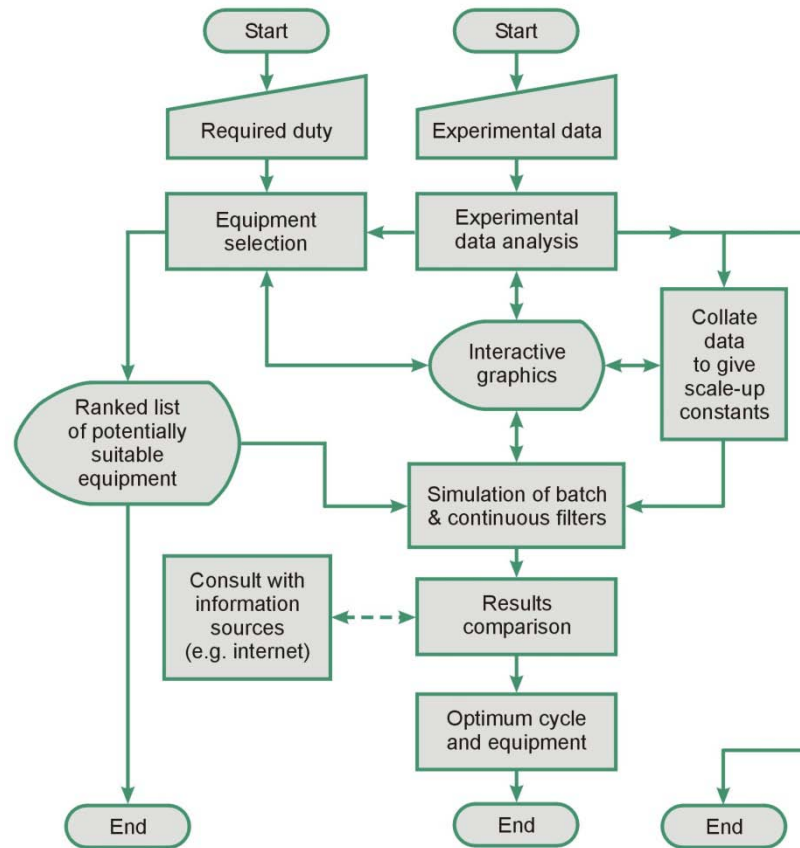


Figure 1: Flowsheet showing the integration of experimentation and computer software in the selection, sizing, simulation and optimisation of solid/liquid separation equipment.

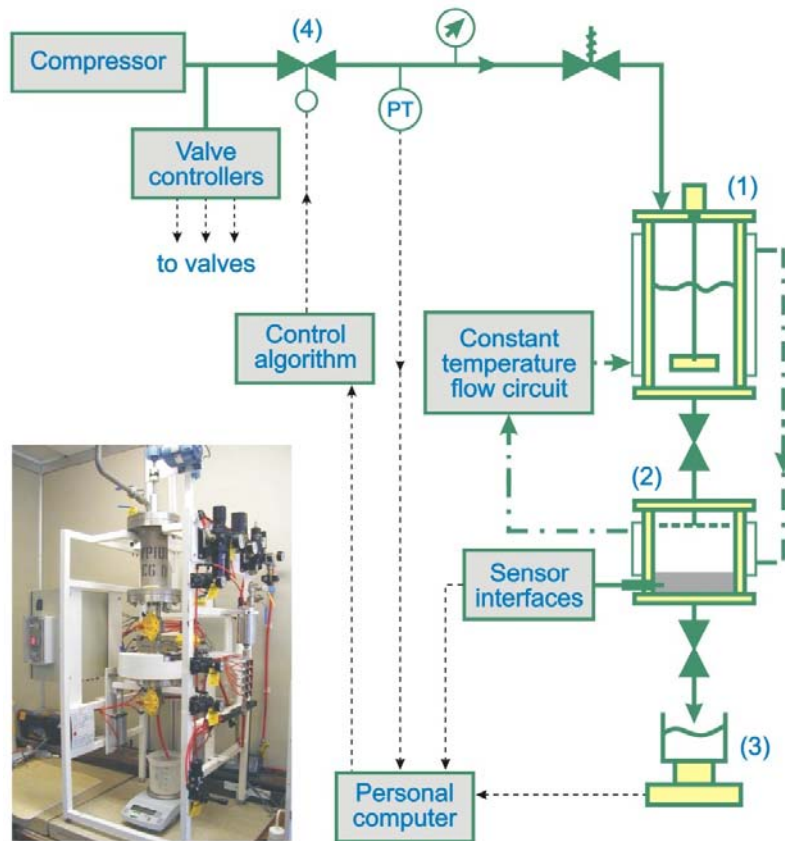


Figure 2: An example apparatus for investigating filtration and gas deliquoring. (1) suspension feed vessel; (2) filter cell, which can be fitted with a range of pressure/electrode sensors; (3) electronic balance; (4) pressure regulator. The addition of a wash feed vessel, sequencing valves and a rotary indexing table facilitates automated measurements of cake washing.

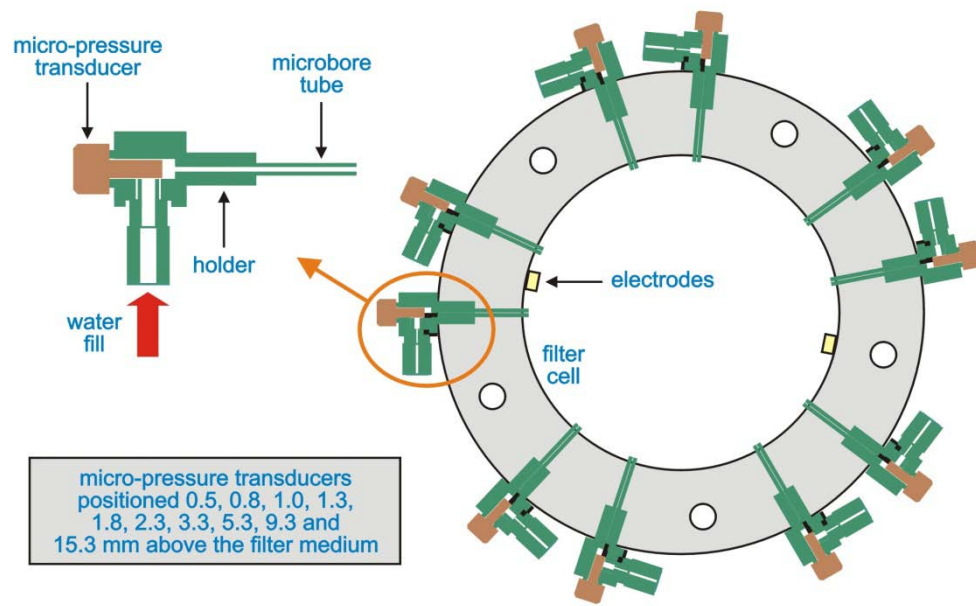


Figure 3: Schematic top view of an example filter cell showing a 10 micro-pressure transducer arrangement together with a single vertical plane of electrode pairings.

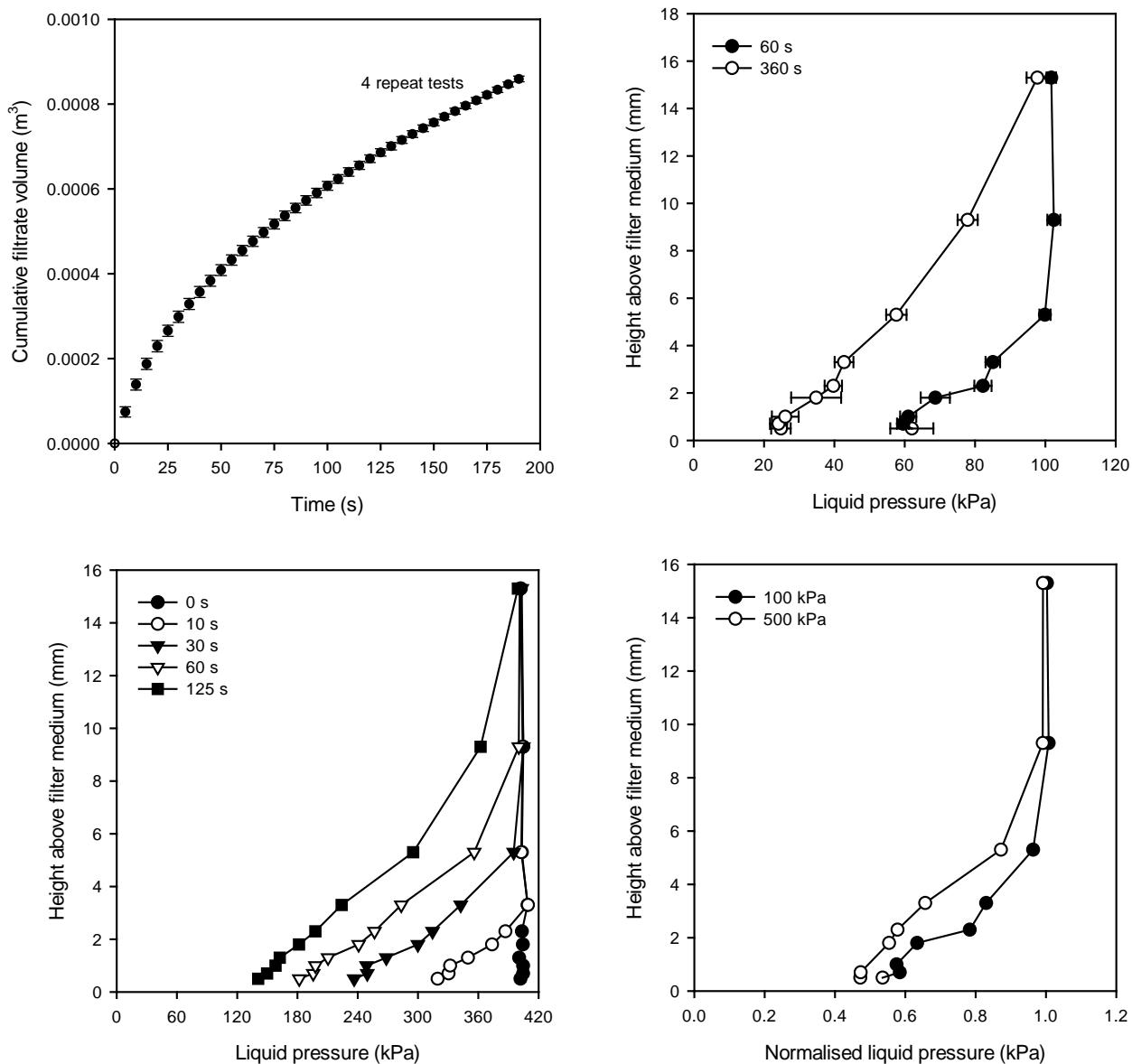


Figure 4: Constant pressure data for aqueous talc suspensions. Repeat  $V$  vs.  $t$  data at 400 kPa filtration pressure (*top left*); repeat experiments showing liquid pressure profiles at 100 kPa filtration pressure (*top right*); liquid pressure profiles in a forming cake at 400 kPa filtration pressure (*bottom left*); normalised liquid pressure profiles after 60 s filtration time (*bottom right*).

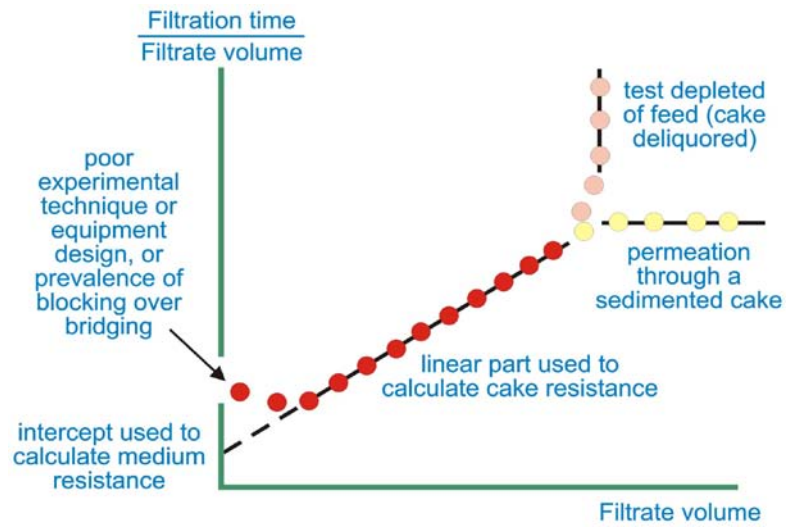


Figure 5: Typical forms of the  $t/V$  vs.  $V$  plot showing examples of where non-linearities can be observed and possible reasons for their occurrence.