

## Loughborough University Institutional Repository

---

### *A new approach to variable pressure filtration*

This item was submitted to Loughborough University's Institutional Repository by the/an author.

**Citation:** TARLETON, E.S., 1998. A new approach to variable pressure filtration. Minerals Engineering, 11 (1), pp. 53-69

**Additional Information:**

- This article was published in the journal, Minerals Engineering [© Elsevier] and the definitive version is available at:  
[http://www.elsevier.com/wps/find/journaldescription.cws\\_home/837/description#description](http://www.elsevier.com/wps/find/journaldescription.cws_home/837/description#description)

**Metadata Record:** <https://dspace.lboro.ac.uk/2134/4825>

**Version:** Accepted for publication

**Publisher:** © Elsevier

Please cite the published version.

This item was submitted to Loughborough's Institutional Repository (<https://dspace.lboro.ac.uk/>) by the author and is made available under the following Creative Commons Licence conditions.



For the full text of this licence, please go to:  
<http://creativecommons.org/licenses/by-nc-nd/2.5/>

## A NEW APPROACH TO VARIABLE PRESSURE CAKE FILTRATION

E.S. Tarleton ([e.s.tarleton@lboro.ac.uk](mailto:e.s.tarleton@lboro.ac.uk))

Department of Chemical Engineering, Loughborough University, Loughborough, Leics., LE11 3TU, UK.

### ABSTRACT

The widespread reliance on heuristics for the design and specification of particle/fluid separation devices has prompted a new, mechatronic based approach to dead-end pressure filtration. A computer driven experimental apparatus was used to facilitate proportionally controlled filtrations over a range of pressure/flow regimes whilst maintaining inherent suspension properties. Preliminary results from constant flow experiments using distilled water and aqueous suspensions of calcite are presented where the air pressure within the filter is controlled through a combination of flow & pressure transducers and an electronically adjusted pressure regulator. The effects of controller type, controller gain, sampling time and set point flow on system response are shown to illustrate what can be achieved using mechatronics. Predictions of constant flow filtration experiments are made using data from constant pressure tests and reasonably good agreement is achieved. A simulation, based on classical filtration and control theories, is also presented and shown to compare well with the filtrate flow responses observed from the filtration apparatus.

### KEYWORDS

Cake filtration; Mechatronics; Control; Simulation; Variable pressure

### INTRODUCTION

Cake filtration has attracted a great deal of academic interest over many years due to its widespread use throughout the chemical and process industries. Whilst research has undoubtedly progressed our understanding, the majority has utilised what must now be considered relatively elementary experimental equipment and been restricted to largely constant pressure investigations. By their natures filtrations are transient processes, usually involving changes in cake properties with time. The resultant need to adjust operational parameters to maintain chosen experimental conditions necessitates outside interference unless appropriate controllers and monitoring equipment are used. Despite an obvious industrial importance, relatively few researchers have attempted to perform laboratory scale filtration experiments at conditions of constant flow and/or variable pressure/variable flow in order to mimic various pumping duties. Those experiments which have been performed have employed either small pumps [1, 2], the manual adjustment of pressure during filtration [3, 4] or specially driven piston presses [5]. With the former it is often difficult to specify suitable pumps and the pumping action can easily change the suspension characteristics due to the presence of shearing forces. The manual adjustment of pressure requires considerable operator skill and dexterity, particularly when filtration conditions are changing quickly whilst a piston press is known to suffer from problems of wall effect. These three approaches have all yielded experimental data in the past, however, there are inherent problems with each which are difficult to reconcile with confidence. Moreover, the experimental difficulties encountered previously with filtration seem to have led recent researchers toward more theoretical work rather than the pursuance of better experimental techniques [6-15].

The work presented in this paper details a new approach to experimental pressure filtration where potentially variable operator interference has been eliminated and replaced by a mechatronics philosophy. The latter, which has evolved and gained interest in recent years, integrates electronics, computer technology, control principles and mechanical systems to improve

processes. Such disciplines have been combined with pressure driven cake filtration to allow a suspension to be filtered in a more repeatable and controlled manner. With appropriate flow monitoring and adjustment of the delivery pressure via computer algorithm, it is shown how leaf filtration can be performed to mimic operation with a positive displacement pump without changing the inherent properties of the feed suspension. This facilitates better predictions of filtration performance and provides a step towards removing heuristics from filter design.

## EXPERIMENT AND CONTROL PHILOSOPHY

To facilitate a mechatronic philosophy within pressure filtration it was necessary to develop the hardware and computer software required to perform experiments over a range of pressure & flow regimes. Figure 1 shows a schematic representation of the fully automated apparatus produced, some parts of which have been previously described in more detail [16]. A stirred stainless steel (s/s) slurry feed vessel was connected via s/s piping and appropriate valving to either a 23 or 80 cm<sup>2</sup> dead-end pressure leaf filter. Sequencing of the valves through an attached personal computer allowed filtration experiments to be performed at test pressures up to 600 kPa. The pressures required to progress filtrations were provided by a dedicated compressor which fed dried and filtered air to both the sequencing valves on the apparatus pipework and an electronic pressure regulator. The regulator could be adjusted by the computer through an appropriate digital-analogue (D/A) signal to implement constant pressure filtration. Continual computer adjustment of the pressure regulator, a suitable control algorithm and flow measurements allowed constant flow and (potentially) variable pressure/flow filtration experiments to be performed; the rate and magnitude of the pressure adjustments being dependent on the nature of the feed and the desired process conditions. Liquor removal rates were monitored via successive timed readings of mass from an electronic balance<sup>†</sup> interfaced to the computer. The balance was capable of delivering up to 10 readings/s to the computer while continual changes were occurring through the transient addition of filtrate. The period between readings was termed the sampling time. The flow rate readings were interpreted by a control algorithm and the filtration pressure adjusted according to the controller settings and the current flow offset. When a deviation from the desired flow conditions was measured the controller would compensate by changing the applied pressure in an attempt to drive the offset to zero.

Although an ideal controller would instantaneously achieve a desired set point flow with no response overshoot, it is almost impossible to achieve this perfection in practice. Instead there is a compromise between set point offset, speed of response and response overshoot which are largely dictated by the type of controller used and the dynamics of the system. The continuous control of a pressure output signal ( $p$ ) can be achieved with a classical three term proportional-integral-derivative (PID) controller such that

$$p = p_s + K \left( \varepsilon + \frac{1}{T_i} \int_0^t \varepsilon dt + T_d \frac{d\varepsilon}{dt} \right) \quad (1)$$

where  $p_s$  is a constant,  $K$  the system gain,  $\varepsilon$  the error (i.e. set point - measured variable),  $t$  is time,  $T_i$  the integral time and  $T_d$  the derivative time. In general terms the proportional action governs the

<sup>†</sup> It is realised that continuous readings from a suitable flowmeter could be used instead of an electronic balance. Whilst a flowmeter has potential benefits its use could also introduce problems of flow restriction and measurement range. The filtrate flows observed in this investigation frequently spanned a range larger than that available from a typical flowmeter and could be very low. To cover the necessary range of flows, two or more flowmeters would be required in addition to suitable switching and flow protection devices. As suitable flowmeters were unavailable, the electronic balance was employed and experiments performed over a range of sampling times to determine its suitability.

speed of response, the integral action improves the accuracy of the final steady state and the derivative action improves the stability [17]. The principles underlying eq. (1) have been applied to the filtration system described to provide for the negative feedback control of constant rate permeations with water and filtrations with 10% v/v calcite suspensions. During a test a pressure was set and remained constant for the given sampling time. The filtrate flow rate was then determined and the filtration pressure required to correct any flow error was calculated via the proportional control algorithm. The required D/A signal was subsequently sent to the pressure regulator to maintain the calculated pressure throughout the next sampling period whence the procedure was repeated.

To determine estimates for the controller settings it was considered appropriate to employ distilled water permeation tests and the open loop reaction curve method attributed to Ziegler and Nichols [18]. Here, the slurry feed vessel was filled with distilled water and the 23 cm<sup>2</sup> filter cell fitted with a new membrane. Permeation proceeded at a fixed pressure for a period of time (to eliminate avoidable transients) after which a step input excitation in system pressure was applied and the open loop flow response measured. Figure 2 shows a typical result where the pressure was raised rapidly from 90 to 360 kPa after 120 s permeation by an appropriate signal to the electronic pressure regulator. The flow response to the step pressure change is indicative of a first order system with a time delay [18] that may be expressed through a transfer function ( $G(s)$ ) of the form

$$G(s) = \frac{k_p \exp(-sT_1)}{1 + T_2 s} \quad (2)$$

where  $T_1$  is the apparent dead time (or transport lag),  $T_2$  the apparent time constant,  $k_p$  the steady-state gain and  $s$  the Laplace operator. The empirical Ziegler-Nichols method was applied to several examples of open loop flow response to give the averaged estimates of controller settings shown in Table 1. The slowly declining flows either side of the step change in pressure on Figure 2 are indicative of a degree of membrane fouling. The fouling arises from the almost negligible amounts of contaminant which accumulate in the feed water during passage through the filtration apparatus.

Filtration data were obtained using 0.2 µm rated Gelman Versapor™ membranes and aqueous suspensions of calcite. Characterisation tests showed the calcite to have respective 10, 50 & 90 % particle sizes of 2.9, 11.3 & 27.1 µm when dispersed in distilled water. The iso-electric point was observed to coincide with a pH = 9.0 whilst a maximum ζ-potential of -20 mV occurred at pH = 10.5 when NaOH was used to alter suspension pH. Scanning electron micrographs revealed a rhomboidal shape and constant pressure filtration experiments indicated a tendency to form relatively incompressible filter cakes. Porometer tests showed typical Versapor membranes to exhibit 10, 50 & 90 % pores sizes of 0.22, 0.25 & 0.27 µm respectively and a tendency to promote cake filtration with calcite suspensions [19]. An approximate hydraulic permeability of  $7 \times 10^{-15} \text{ m}^2$  was determined in a series of constant pressure water permeation experiments, using an average measured thickness equal to 185 µm.

## EXPERIMENTAL RESULTS

The experimental results conveniently divide into two parts. Figures 3-5 show results from tests using distilled water where flows are controlled to provide for constant permeation rates within the 23 cm<sup>2</sup> filter cell. These data were used to give a general indication of system behaviour as controller settings were altered. Figures 7-9 show data for 10% v/v distilled water calcite suspensions where the 80 cm<sup>2</sup> filter cell was used in conjunction with software control to promote constant rate filtrations.

Permeation tests with distilled water indicated that the variables controller type, controller gain, set point flow, initial pressure and sampling time were important in determining adequate responses from the filtration apparatus. Figure 3 shows the typical form of a flow response when a negative feedback proportional controller was employed with a sampling time of 20 s and a proportional gain of  $5 \times 10^4$ . The initial overshoot flow response is followed by a decaying oscillatory response until the flow settles to within  $\pm 5\%$  of the set point after approximately 400 s. During the oscillatory period of the test the system pressure changed between the initial value of 100 kPa & 10 kPa and settled at a value of 40 kPa @  $t = 400$  s, after which the pressure slowly increased in order to compensate for slow fouling of the membrane. The pressure tended to change more rapidly in the early stages of permeation in response to the larger control action. Although the response shown in Figure 3 may be considered reasonable in some instances, the relatively long response time would be unacceptable in a corresponding experiment with a suspension as cake properties could be influenced over the initial period of greatest pressure fluctuations. The issue of 'good' control has attracted interest in the control literature and several measures can be applied to give 'figures of merit' such as ISE, IAE and ITAE [18]. For a filtration apparatus it is considered more appropriate to achieve a rapid control of flow rather than potentially sacrificing good response time to reduce relatively small flow offsets. By doing so cake formation can proceed in the required manner at a known, and steady, filtrate flow rate. Proportional control matches such criteria and the results presented in the remainder of this paper for permeation and filtration utilise this form of control algorithm. When proportional-integral control was used in the water permeation tests a constant flow at the set point could be achieved. However, a greater oscillatory response period was observed in conjunction with an increased response time. In principal, a proportional-derivative controller should give both a reduced overshoot and response time as well as improved stability. Whilst this was generally found to be the case, the benefits to be gained were relatively small for the range of trial and error derivative settings tried. It was felt more profitable at this stage to investigate the mechatronics philosophy through proportional control and leave controller optimisation for future development.

Figure 4 shows how the response time in a water permeation test was typically influenced by the sampling time for a set point flow of  $2 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ . At lower sampling times ( $< 10$  s) the flow response was purely oscillatory indicating that the time delay, observed in the open loop reaction curve (Figure 2), had a significant effect on the stability of the system. As the sampling time was increased both the number of oscillations and the response time were reduced until a minimum response time was observed in the range 20-30 s. At longer sampling times the response time increased again due to the extended time required to obtain flow readings and thus establish control. Figure 5 shows how the magnitude of the proportional gain typically affected response time and average flow offset. At lower values of gain the response time was very slow and exceeded the time frame of the experiment in some cases. As the gain was increased so both the response time and flow offset were reduced. For the experimental conditions a minimum response time was observed at a gain approximately one third the value suggested by the Ziegler - Nichols method. At larger values of gain the controller tended to saturate and the flow response became oscillatory. It is noted in passing that the rise time was reduced as the proportional gain was raised. The least overshoot in flow response was observed when an initial pressure close to the theoretical Darcy pressure required for water flow at the set point through a new membrane was used.

In most water permeation tests the Ziegler - Nichols settings provided reasonable estimates for constant flow control. As it was difficult to directly apply the Ziegler - Nichols methodology with filtering suspensions, due to the added complexity of significant cake formation, the information determined from the water permeation test was used as a basis for the filtration experiments. Figure 6 shows sample filtration data where proportional control was used to maintain a 10% v/v calcite filtration at 'constant rate' conditions with a set point flow of  $4 \times 10^6 \text{ m}^3 \text{ s}^{-1}$  and a gain of  $1 \times 10^5$ . The behaviour is again typical of proportional control whereby the overshoot response observed toward the start of filtration is followed by a decaying oscillatory response. For the test shown the latter resulted in a near constant filtrate flow at a fixed offset of  $\sim 10\%$  from the set point.

During the constant rate period the filtration pressure increased in an essentially linear manner in accordance with classical filtration theory [20] with a typical experiment showing a regression coefficient in excess of 0.99. Where the maximum system pressure was reached constant pressure filtration commenced and the filtrate flow rate decayed until the end of the experiment. It is apparent from Figure 6, and other similar data, that the presence of significant solids within the feed suspension alters the control characteristics of the apparatus. In comparison with water permeation tests under similar conditions, the response time was generally found to be reduced at the expense of an increased offset from the desired set point flow. The latter observation is in direct contrast to the water permeation tests where little flow offset generally occurred. It is thought that the proportional controller is incapable of responding to the demands imposed by the growing filter cake, a situation which could potentially be eliminated by moving to other, more sophisticated, control algorithms.

Figure 7 shows typical examples of how flow response altered as proportional gain was changed over the range  $5 \times 10^4$ – $6 \times 10^5$ . At lower values of gain the action of the control algorithm was sufficiently small to ensure little overshoot response. However, the steady-state offset from the set point flow was relatively large and the flow control was generally considered to be poor. As the gain was increased so the response time<sup>†</sup> changed at the expense of greater overshoot and more oscillations about the reduced offset flow. At yet higher gains the flow response became unsatisfactory due to larger pressure fluctuations and sufficiently good control could not typically be established within the relatively small time frame of an experiment. Although such behaviour is to be expected from a proportional control algorithm, the influence of gain on flow response was complicated by a dependency on other factors including the desired set point flow, the pressure used to initiate filtration and the sampling time.

Figure 8 shows the effects of changing the required set point flow with a sampling time of 20 s. For an experiment performed at the lowest set point of  $2 \times 10^{-6} \text{ m}^3 \text{ s}^{-1}$  (not shown), the flow response was unacceptable with a response time in excess of 300 s, or 15 sampling time intervals. Both the pressure and flow response showed considerable oscillation over the initial period of the experiment, to the obvious detriment of controlled cake formation. Experiments performed at intermediate set point flows showed significantly less pressure and flow oscillations in conjunction with improved response times approaching 100 s (~5 sampling time intervals). As set point flow was increased yet further the response time continued to improve and tests at a set point flow of  $6 \times 10^{-6} \text{ m}^3 \text{ s}^{-1}$  showed that suitable control could be achieved within 3–4 sampling time intervals. Although response time was generally reduced as the required set point flow was increased, this was at the expense of flow offset. Over the flow set point range  $2 \times 10^{-6}$ – $6 \times 10^{-6} \text{ m}^3 \text{ s}^{-1}$  the constant flows achieved progressively decreased from 95–81 % of the desired flow, with the actual flow always being below the desired flow. Such a facet, although ultimately undesirable, is more of a nuisance than a problem to render experiments unacceptable, as analysis of such filtrations would utilise the constant flow achieved rather than the desired set point flow.

Figure 9 illustrates the typical effects of altering sampling time over the range 5–30 s. In general terms a reduced sampling time provided for an improved response time, primarily due to the lesser time required to take a given number of samples. For the experimental conditions shown a 5 s sampling time yielded reasonable flow control within 20 s of the start of the filtration and a flow response within  $\pm 5\%$  of the  $3 \times 10^{-6} \text{ m}^3 \text{ s}^{-1}$  set point. Conversely, longer sampling times typically showed a number of oscillations around the set point flow and deviations greater than 5%. It was inferred earlier that the presence of solids in the feed tended to make the filtration apparatus behave in a more stable manner. This is confirmed by the data shown in Figure 9 as constant flow water permeations with sampling times less than 10 s led to pure oscillatory responses. The investigations of sampling time indicated a potential compromise between controller response and

<sup>†</sup> In the context of filtration, response time is defined as the time required for the initial flow oscillations to settle within  $\pm 5\%$  of the ultimate constant flow achieved, rather than the time required to achieve a flow within  $\pm 5\%$  of the set point.

the reliability of flow measurement. At shorter sampling times, smaller amounts of filtrate are collected in a given time. This situation is likely to intensify with more difficult to filter suspensions and it is clear how relatively minor perturbations in filtrate flow can significantly influence the reliability of flow measurement. With longer sampling times there is less likelihood of significant disturbance from short perturbations, however, the times required to achieve control are likely to be longer. This trade-off between flow measurement reliability and speed of control is a problem inherent in the use of an electronic balance and is discussed in more detail later.

## DISCUSSION

The data shown in Figures 2-9 illustrate how the mechatronics philosophy can be applied to variable pressure filtration. Whilst the data are useful they are only representative of a methodology and a start towards the removal of heuristics from filter testing, sizing and scale-up. The ability to control filter operation over a range of pressure/flow regimes is obviously important, however, in the context of this paper control can facilitate filtrations where suspensions are treated in identical manners to allow the use of suitable performance analyses. In the following, example analyses are made using a combination of classical filtration and control theories. The analyses serve to highlight how sensible predictions of filter performance can be made when reliable data are available and how mechatronics might benefit future filtration research.

Classical filtration theory, although often dismissed within academia, is still widely used by commercial organisations to analyse filtration data. For constant flow filtration, classical theory states that the filtration time ( $t_f$ ) is related to the filtration pressure ( $\Delta p$ ) by

$$t_f = \frac{A^2 (1 - M_s (1 + e_{av} (\rho/\rho_s)))}{\alpha_{av} \mu \rho M_s Q^2} \left( \Delta p - \mu R_m \frac{Q}{A} \right) \quad (3)$$

where  $\alpha_{av}$  is the average specific cake resistance,  $e_{av}$  the average cake voids ratio,  $A$  the filter area,  $\mu$  the filtrate dynamic viscosity,  $M_s$  the solids mass fraction in the feed,  $\rho$  the filtrate density,  $\rho_s$  the solids density,  $R_m$  the filter medium resistance and  $Q$  the (constant) filtrate flow rate. The values of the four scale-up constants used to evaluate  $\alpha_{av}$  and  $e_{av}$  in eq. (3) are most frequently derived empirically from sequences of individual constant pressure filtration experiments [19]. It has previously been shown by the author [16] using constant pressure filtrations that  $\alpha_{av}$  values for calcite range between  $1.1$ - $1.5 \times 10^{10} \text{ m kg}^{-1}$  and  $e_{av}$  values range between  $1.74$ - $1.44$  over the pressure region  $100$ - $600 \text{ kPa}$ . The combination of eq. (3) with the proportional control part of eq. (1) generated the flowsheet algorithm shown in Figure 10 and allowed the operation of the filtration apparatus to be simulated over the necessary range of experimental conditions. A computer simulation based on the flowsheet in Figure 10 was written using the values of the scale-up constants  $\alpha_0$ ,  $n$ ,  $e_0$  and  $b_1$  known previously from the constant pressure experiments [16] and eq. (3) by substituting

$$\Delta p_c = \Delta p - \Delta p_m = \Delta p - \frac{\mu R_m Q}{A} \quad (4)$$

to give

$$Q^2 = \frac{A^2 (1 - M_s (1 + (\rho/\rho_s)(e_0 - b_1 \log(\Delta p_c))))}{\mu \rho M_s t_f \alpha_0 (1 - n)} \Delta p_c^{1-n} \quad (5)$$

where  $\Delta p_c$  and  $\Delta p_m$  are the pressure gradients across the filter cake and medium respectively. Figure 11 shows a typical comparison between experimental and simulated flow & pressure responses for a calcite filtration with a set point flow of  $3 \times 10^{-6} \text{ m}^3 \text{ s}^{-1}$ . The theoretical prediction of



flow is relatively good, particularly for flow offset and response time. The prediction of pressure response is reasonably good over the initial period, however some deviation occurs toward the end of the filtration period. Figure 12 shows how proportional gain influences both response time and flow offset for calcite filtrations. Figure 7 suggested that flow offset is reduced as the controller gain is increased and this is confirmed in Figure 12 where predicted values are very close to the experimentally observed values. Although the predicted trend for response time is correct in the general sense, the theoretical values are significantly different to the experimental values at larger values of gain, indicating that the simulation may not be able to provide suitable predictions over the region where control was generally unacceptable.

An essential part of the filtration apparatus control system was provided by the electronic balance used to monitor filtrate flows. Although the balance provided a potential transport lag in the measurement, and hence control, system it was found to give robust and acceptable operation over a wide range of flows. In order to reduce the effects of unwanted transients the balance included an in-built averaging algorithm to give a potential accuracy of 0.07 g in 4 kg when the weighing pan was allowed to stabilise for 2.5 s. Throughout a filtration test the filtrate was continually added to a container on the weighing pan at a changing rate and thus stabilisation times of 2.5 s could not be realised. The potential for errors in the transient flow rate readings was investigated using a modified version of the simulation algorithm presented in Figure 10. A random flow rate error of up to  $\pm 10\%$  was artificially introduced to the simulation and the results for a  $\pm 5\%$  random error in each flow rate reading are shown in Figure 13. Comparisons between the simulation data on Figures 11 and 13 suggest that the errors introduced using the electronic balance are likely to be less than  $\pm 5\%$  and the simulation suggested that the actual errors are substantially less than  $\pm 2\%$ . It is difficult to be sure of the degree of transient error introduced by the balance due to the natural fluctuations from the control algorithm. However, the author believes the approach taken is at least as good as, for instance, using Pelton wheel flowmeters on the filtration apparatus and potentially more robust and flexible. Pelton wheel flowmeters, although capable of rapidly monitoring flows down to at least 0.01 l/min with an accuracy better than  $\pm 0.5\%$  of full scale, are generally sensitive to the presence of particles, have relatively low turndown ratios, suffer from larger inaccuracies at lower flows and generate relatively large (and unacceptable) pressure drops.

The ability to predict filter performance by computer algorithm is of obvious benefit to the researcher and design engineer alike. Although some progress has recently been made in this area [11, 21, 22], it is still recommended practice for variable pressure filtration performance to be empirically predicted from a knowledge of constant pressure filtration behaviour, sometimes with the addition of 'factors of safety' [23]. Figure 14 illustrates how the procedure can be applied to some of the experimental data presented. In Figure 14 the pressure responses corresponding to the sets of flow responses in Figure 8 are compared with predictions made from the classical filtration theory presented in eq. (3) and known scale-up constant values [16]. No control algorithm is included in this case as eq. (3) was simply evaluated at a range of time's for the known process conditions to produce corresponding sequences of pressures. The predicted changes in pressure with time for all set point flows are reasonably close to the experimentally measured values with the data at the higher set point flows showing the greatest deviations. Here, the filtration pressures are higher and, although calcite forms cakes of relatively low compressibility, it is possible that particle rearrangements induced in the growing cake take a short but finite time to occur. If such particle relaxation does significantly influence variable pressure filtration then the degree of influence is likely to increase with increasing cake compressibility. This suggestion may cast some doubt on the ability of constant pressure data acquired under essentially 'static' conditions to predict variable pressure filtrations where more 'dynamic' conditions prevail. Whilst a few researchers have described their opinion on these matters previously [2, 3, 24-26], none have arrived at definitive conclusions, and the subject of variable pressure filtration must be considered a priority in future filtration research.

As the work presented is at a relatively early stage of development it is probably premature to draw any definitive conclusions, however, the potential of the mechatronics approach is clear. The work undertaken has produced and utilised a single, fully automated, computer controlled, apparatus to facilitate repeatable experiments that mimic the operation of industrial filtrations using positive displacement and (potentially) centrifugal pumps. In the wider context separations can be performed at laboratory or semi-technical scales through any chosen pressure/flow regime without changing the properties of the feed in an inappropriate, and un-quantifiable, manner. The characterising parameters for each mode of filtration can be determined under well controlled, dynamic conditions, without resorting to the sequences of essentially static experiments currently employed. Moreover, these parameters can be directly compared with a degree of confidence and the inter-relations which exist thus determined.

## CONCLUSIONS

The ability to generate reliable experimental data is a prerequisite to understanding filtration processes. With the advent of mechatronics technologists now have the opportunity to both examine filtration processes in new, novel and more accurate ways and remove the heuristics from the design and specification of filters. In this paper it has been shown how mechatronic principles can be utilised to provide automated experiments over a range of filtration conditions and feed materials without changing the characteristics of feed suspensions. It has also been shown how a computer simulation can predict separation performance over the constant flow regime when reliable scale-up parameters are available. Although some comparisons of constant pressure and constant flow filtrations have been presented to show the principles of what can be achieved, more work is required before significant conclusions can be drawn. The correct combinations of hardware, software and control philosophies need to be developed to manipulate pressures and/or flows accurately and quickly over wide ranges in reliable and repeatable manners. With these in place it should prove possible to quantify filtration characteristics in better forms, thus allowing for more accurate scale-up methodologies and less reliance on heuristics.

## ACKNOWLEDGEMENTS

The author would like to acknowledge the financial support of Dupont for funding parts of the research presented in this paper.

## NOMENCLATURE

$A$	filter area ( $\text{m}^2$ )
$e_{av}$	average cake voids ratio (-)
$G(s)$	system transfer function
$k_p$	steady state gain
$K$	system gain
$M_s$	solids mass fraction in the feed (-)
$p$	pressure (Pa)
$\Delta p$	filtration pressure (Pa)
$\Delta p_c$	filtration gradient across the cake (Pa)
$\Delta p_m$	filtration gradient across the filter medium (Pa)
$Q$	filtrate flow rate ( $\text{m}^3 \text{s}^{-1}$ )
$Q_s$	flow set point ( $\text{m}^3 \text{s}^{-1}$ )
$R_m$	filter medium resistance ( $\text{m}^{-1}$ )
$s$	Laplace operator
$t$	time (s)
$t_f$	filtration time (s)

$T_1$	apparent dead time (s)
$T_2$	apparent time constant (s)

#### Greek symbols

$\varepsilon$	flow error ( $\text{m}^3 \text{s}^{-1}$ )
$\mu$	filtrate dynamic viscosity (Pa s)
$\rho$	filtrate density ( $\text{kg m}^{-3}$ )
$\rho_s$	solids density ( $\text{kg m}^{-3}$ )
$t_d$	derivative time (s)
$t_i$	integral time (s)

## REFERENCES

1. Harvey M.A., Bridger K. and Tiller F.M., Apparatus for studying incompressible and moderately compressible cake filtration, *Filt. and Sep.*, **23**(1), 21 (1986).
2. Tiller F.M., The role of porosity in filtration Part 3: Variable-pressure variable-rate filtration, *AIChEJ*, **4**(2), 170 (1958).
3. Shirato M., Aragaki T., Iritani E. and Funahashi T., Constant rate and variable pressure - Variable rate filtration of power-law non-Newtonian fluids, *J. Chem. Eng. Japan*, **13**(6), 473 (1980).
4. Shirato M. and Aragaki T., Verification of internal flow mechanism theory of cake filtration, *Filt. and Sep.*, **9**(3), 290 (1972).
5. Murase T., Iritani E., Hattori M., Kobayashi K. and Shirato M., Variable-pressure filtration of power-law non-Newtonian fluids on cylindrical surfaces, *J. Chem. Eng. Japan*, **20**(6), 632 (1987).
6. Bourgeois F.S. and Lyman G.J., Morphological analysis and modelling of fine coal filter cake structure, *Chem. Eng. Sci.*, **52**(7), 1151 (1997).
7. Stahl W. and Nicolaou I., Calculation of rotary vacuum plant, *Industrie Minerale Mines et Carrieres Les Techniques*, **3/91**, 14 (1991).
8. Nystrom L.H.E., Simulation of disc filter for the pulp and paper industries, *Filt. and Sep.*, **30**(6), 554 (1993).
9. Stamatakis K. and Tien C., Cake formation and growth in cake filtration, *Chem. Eng. Sci.*, **46**(8), 1917 (1991).
10. Kamst G.F., Bruinsma S.L. and de Graauw J., Permeability of filter cakes of palm oil in relation to mechanical expression, *AIChEJ*, **43**(3), 673 (1997).
11. Wakeman R.J. and Wei X., Simulating the performance of tilting pan filters, *Filt. and Sep.*, **32**(10), 979 (1995).
12. Wu Y., An analysis of constant pressure filtration, *Chem. Eng. Sci.*, **49**(6), 831 (1994).
13. Lee D.J., Filter medium clogging during cake filtration, *AIChEJ*, **43**(1), 273 (1997).
14. Tien C., Bai R. and Ramarao B.V., Analysis of cake growth in cake filtration: Effect of fine particle retention, *AIChEJ*, **43**(1), 33 (1997).

15. Lu W-M, Tung K-L and Hwang K-J, Effect of woven structure on transient characteristics of cake filtration, *Chem. Eng. Sci.*, **52**(11), 1743 (1997).
16. Tarleton E.S. and Hancock D.L., Using mechatronics for the interpretation and modelling of the pressure filter cycle, *Trans. IChemE*, **75**(A), 298 (1997).
17. Fraser C. and Milne J., *Integrated Electrical and Electronic Engineering for Mechanical Engineers*, McGraw-Hill, New York (1994).
18. Coughanowr D.R., *Process Systems Analysis and Control*, McGraw-Hill, New York (1991).
19. Tarleton E.S. and Willmer S.A., The effects of scale and process parameters in cake filtration, *Trans. IChemE*, **75**(A), 497 (1997).
20. Tarleton E.S., Predicting the performance of pressure filters, *Proc. Filtech Conference*, Filtration Society, Dusseldorf, (1997), *in press*.
21. Wakeman R.J. and Tarleton E.S., A framework methodology for the simulation and sizing of diaphragm filter presses, *Min. Eng.*, **7**(11), 1411 (1994).
22. Wakeman R.J. and Tarleton E.S., Simulation and process design of the filter cycle, *Filt. and Sep.*, **27**(6), 412 (1990).
23. Purchas D.B. and Wakeman R.J., *Solid/Liquid Separation Equipment Scale-up (2<sup>nd</sup> Edn.)*, Uplands Press, London (1986).
24. Walas S.M., Resistance to filtration, *Trans. Am. Inst. Chem. Engrs.*, **42**, 783 (1946).
25. Carman P.C., Fundamental principles of industrial filtration, *Trans. Am. Inst. Chem. Engrs.*, **16**, 168 (1938).
26. Arora M.L., Constant-rate and constant-pressure filtration look similar - but are they, *AWWAJ*, **May**, 267 (1978).

## FIGURES AND TABLES

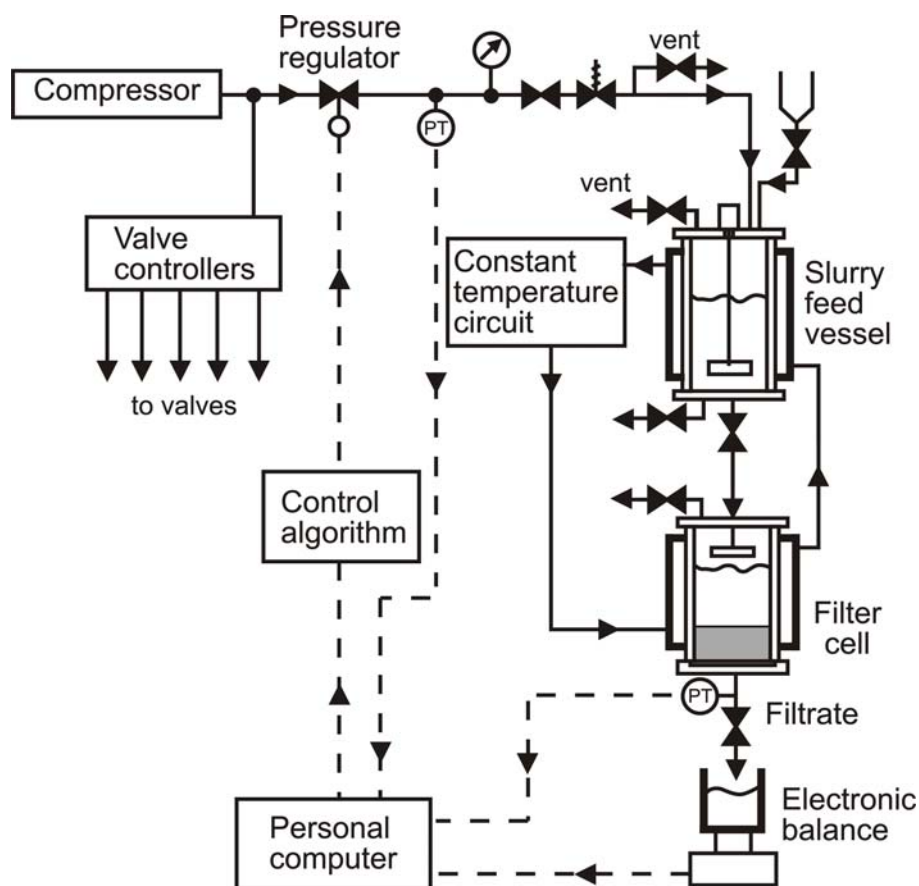


Figure 1: Schematic representation of the computer controlled filtration apparatus.

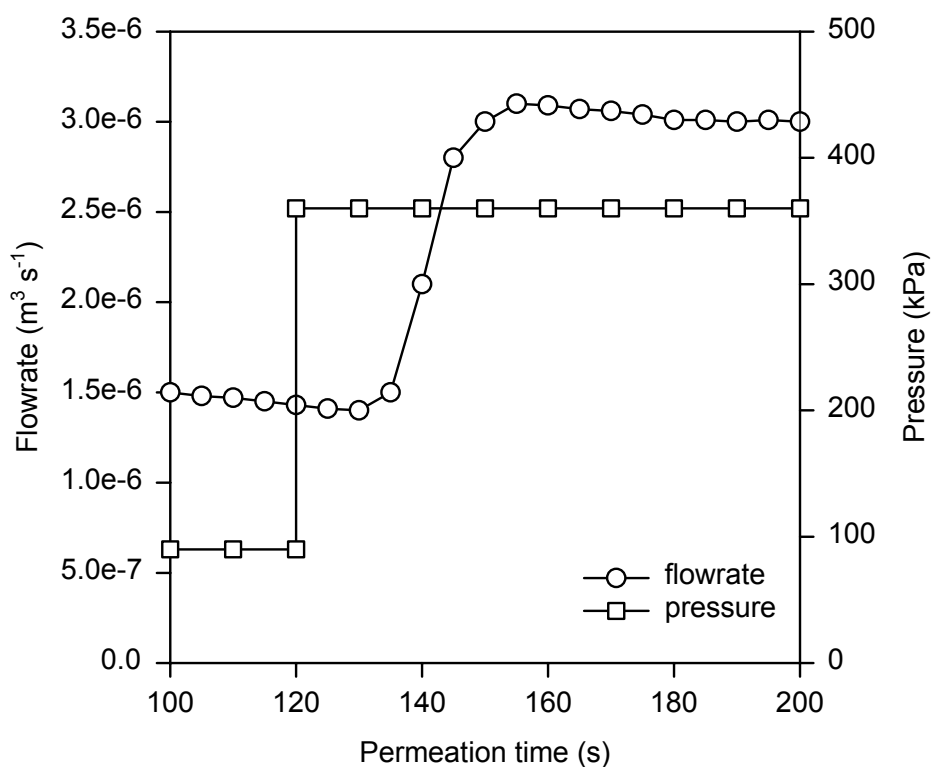


Figure 2: A typical open loop reaction curve for water permeation subject to a step pressure change.

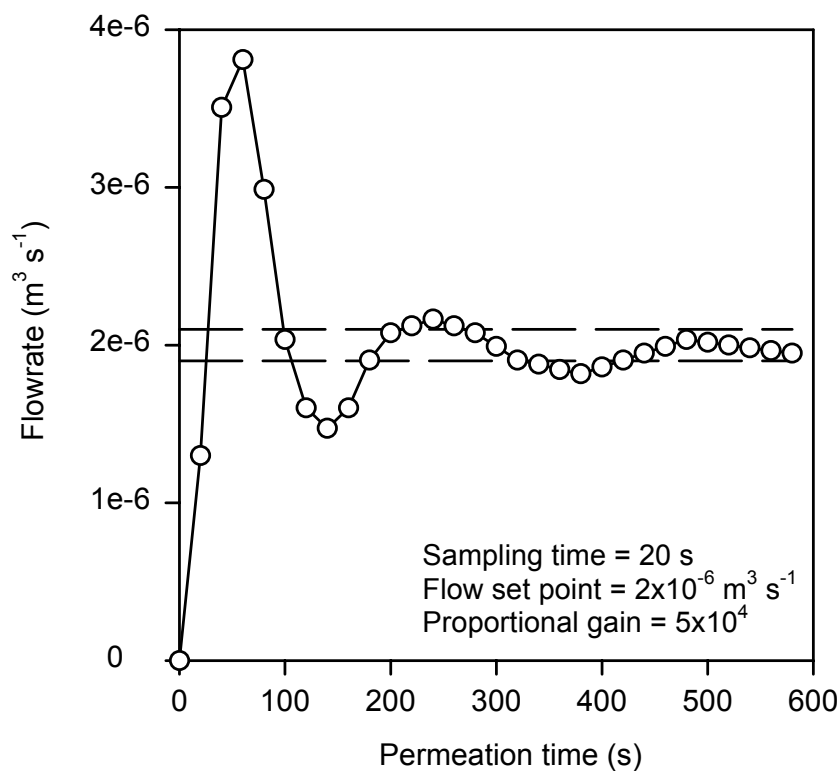


Figure 3: Typical flow response for water permeation with a negative feedback proportional controller.

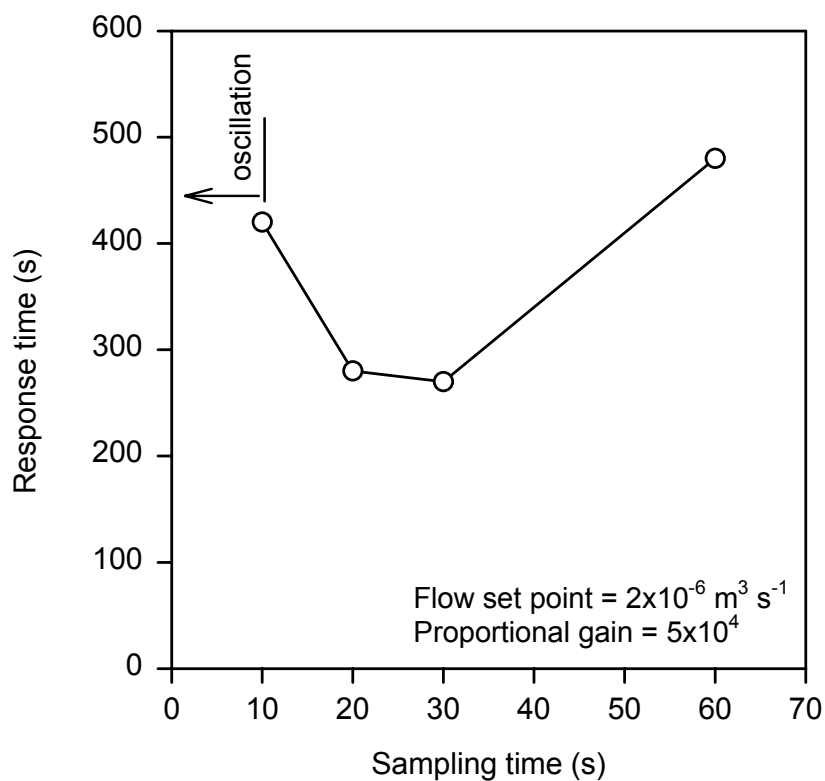


Figure 4: Influence of sampling time on response time for water permeation.

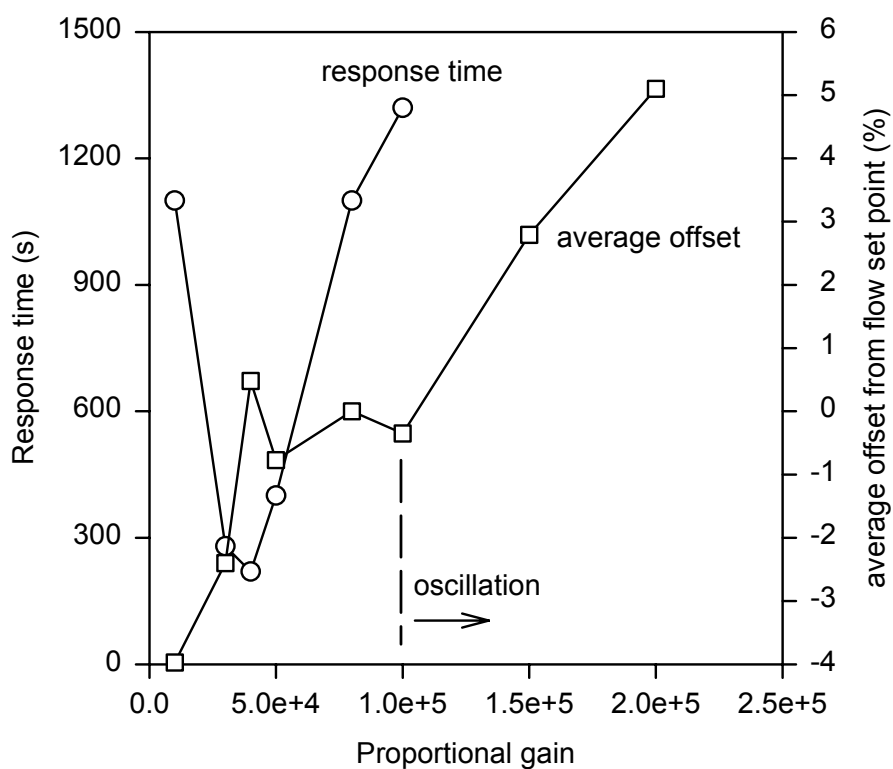


Figure 5: Effect of proportional gain on response time and flow offset for water permeation.

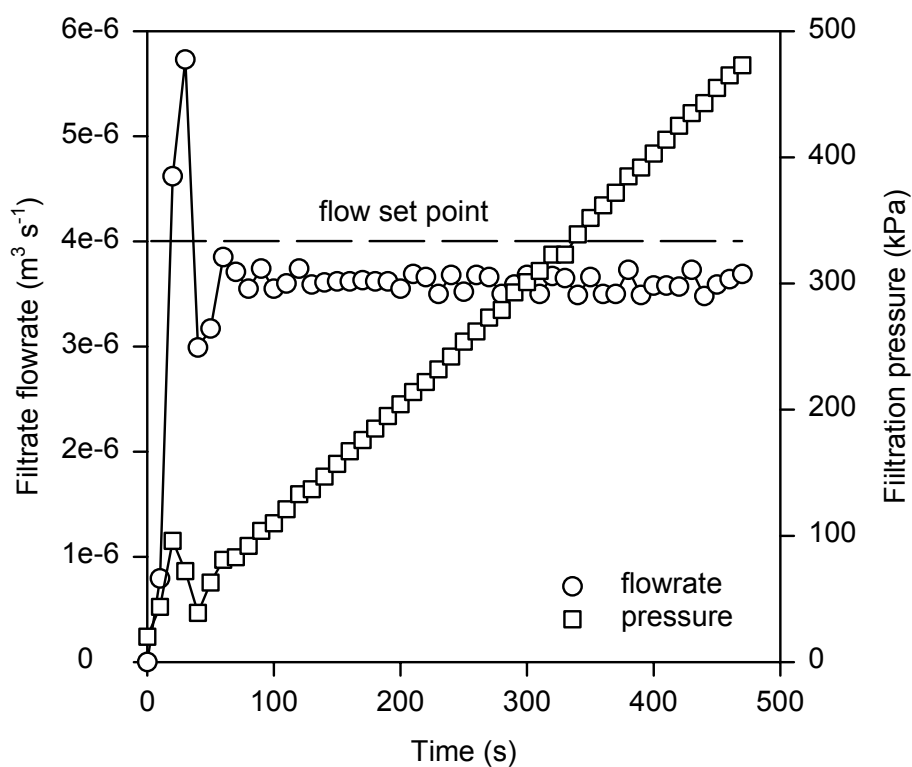


Figure 6: Pressure and filtrate flow rate histories for the proportionally controlled filtration of a calcite suspension.

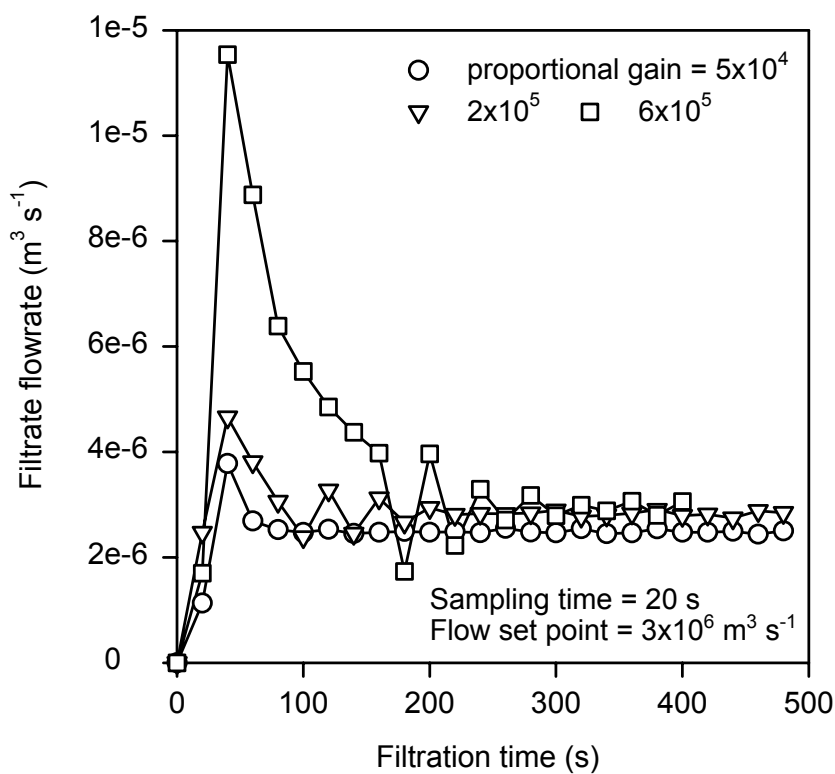


Figure 7: Effect of controller proportional gain on flow response for calcite suspensions.



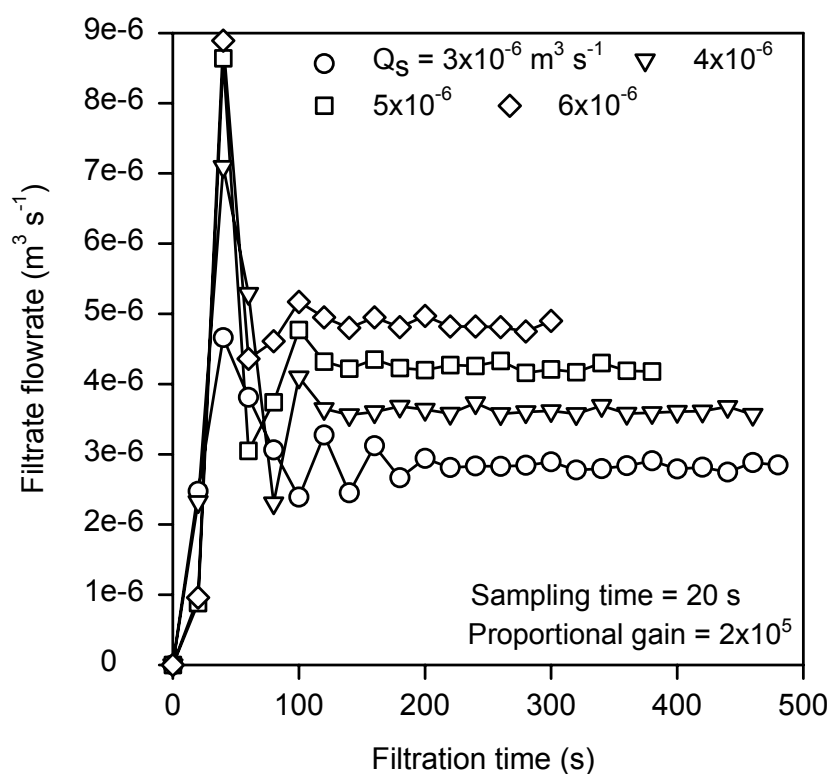


Figure 8: Effect of flow set point ( $Q_s$ ) on flow history for calcite suspensions.

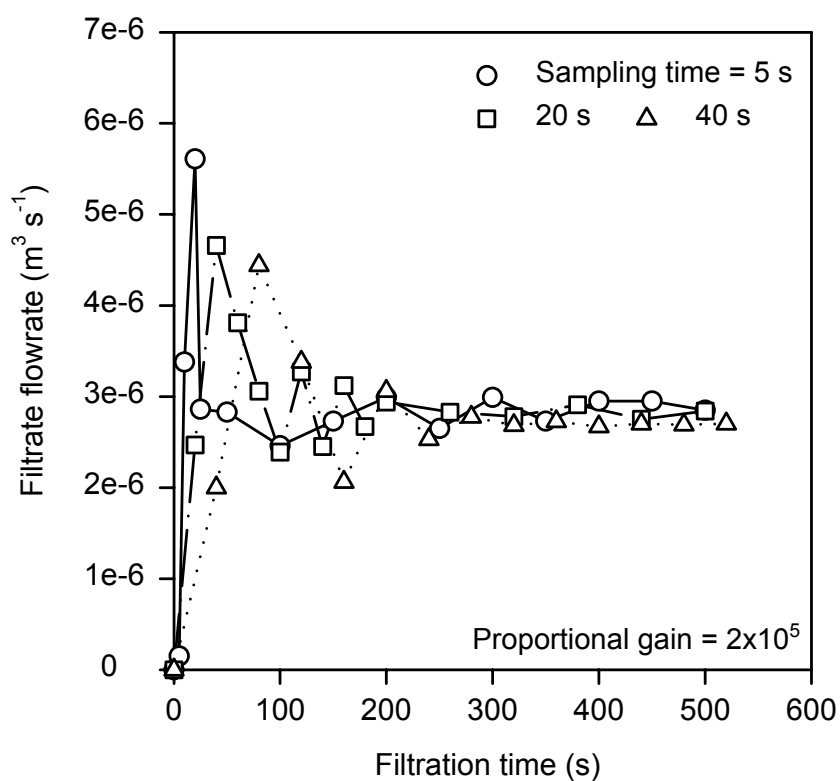


Figure 9: Effect of sampling time on flow response for calcite suspensions.

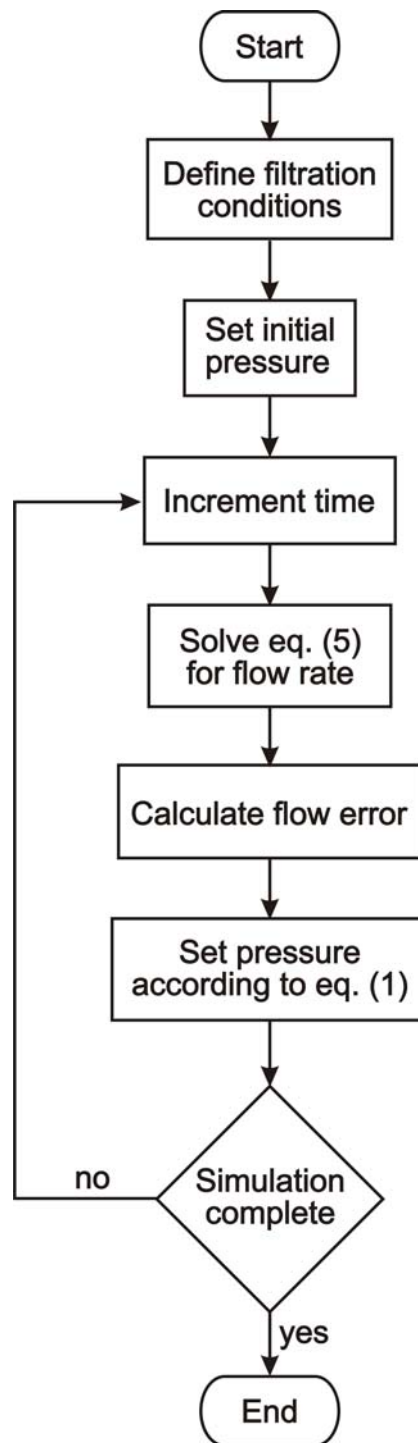


Figure 10: Outline flowsheet for the simulation of constant flow filtration.

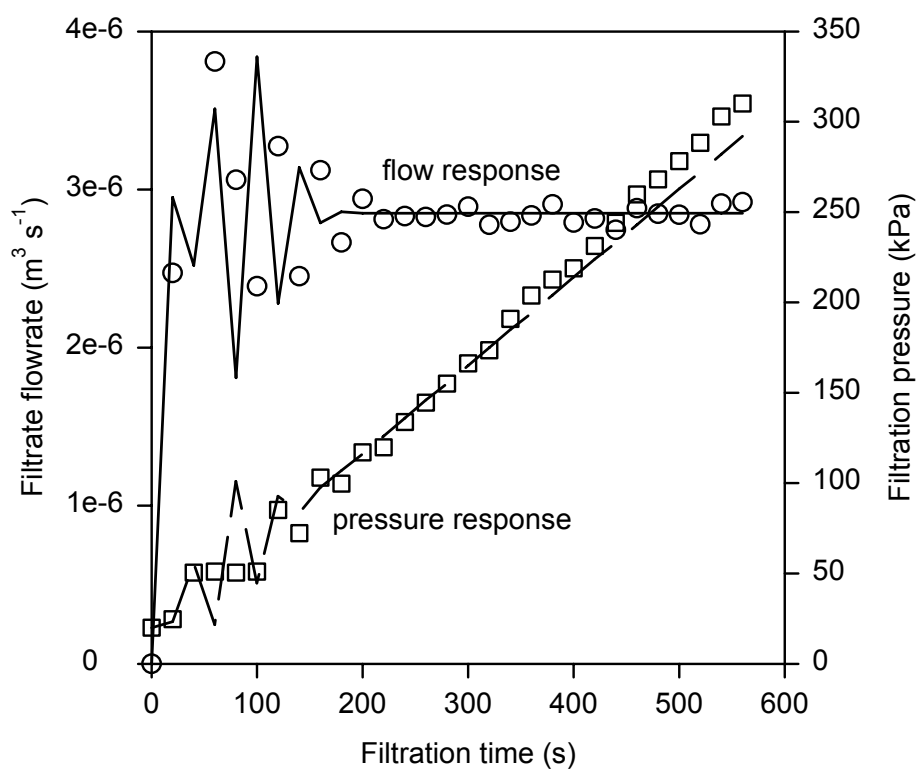


Figure 11: Theoretical predictions of flow and pressure response for a calcite filtration.

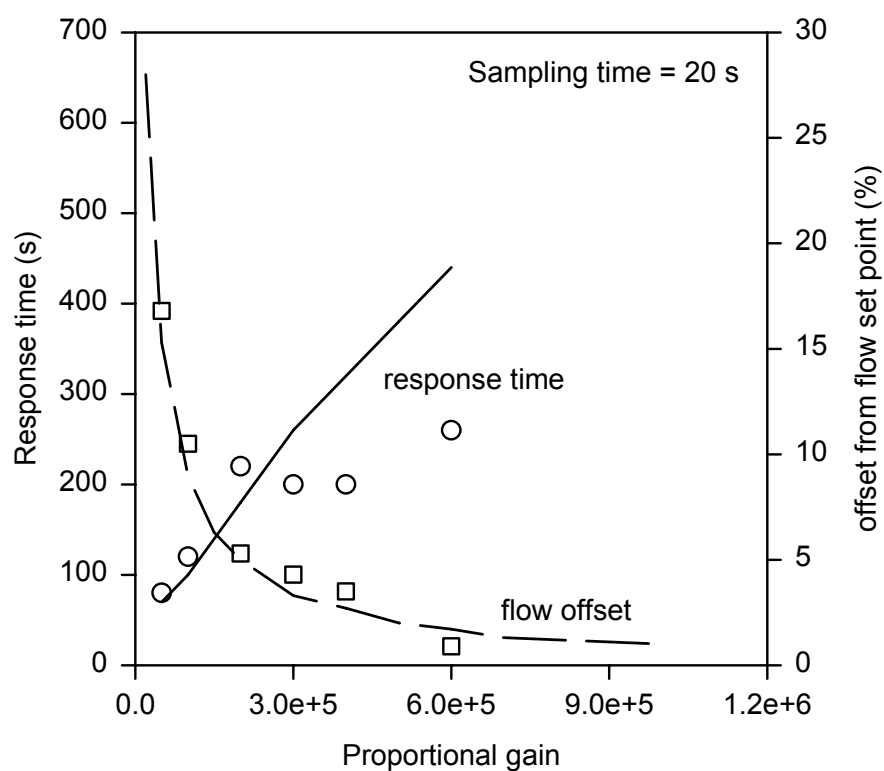


Figure 12: The effects of controller gain on response time and flow offset for calcite filtrations.

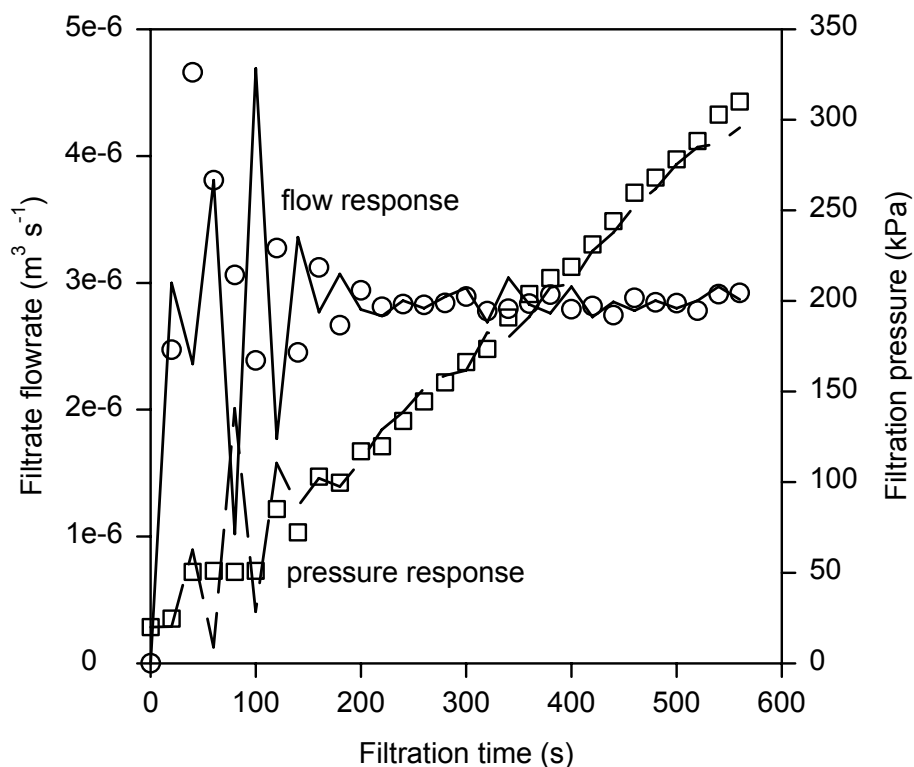


Figure 13: Theoretical effect of flow perturbations of  $\pm 5\%$  on flow response (same experimental data as Figure 11).

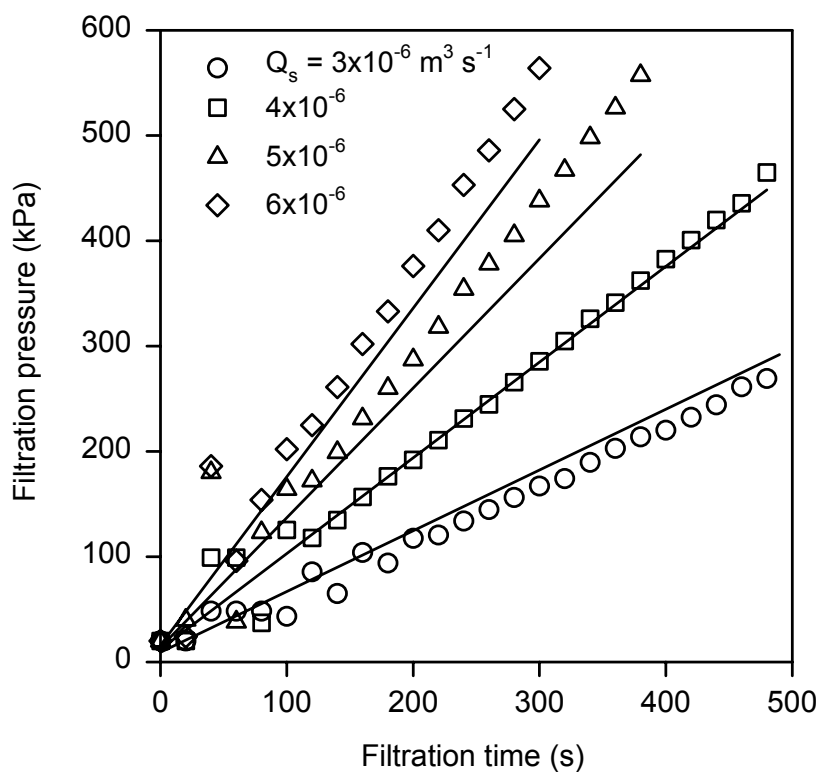


Figure 14: Comparisons of experimental constant flow data and predictions made using classical filtration theory.

Controller type	$K$	$\tau_I$ (s)	$\tau_d$ (s)
P	$1.22 \times 10^5$	-	-
PI	$1.10 \times 10^5$	71.8	-
PID	$1.47 \times 10^5$	43.1	10.8

Table 1: Initial estimates of controller gains using the empirical Ziegler-Nichols method.