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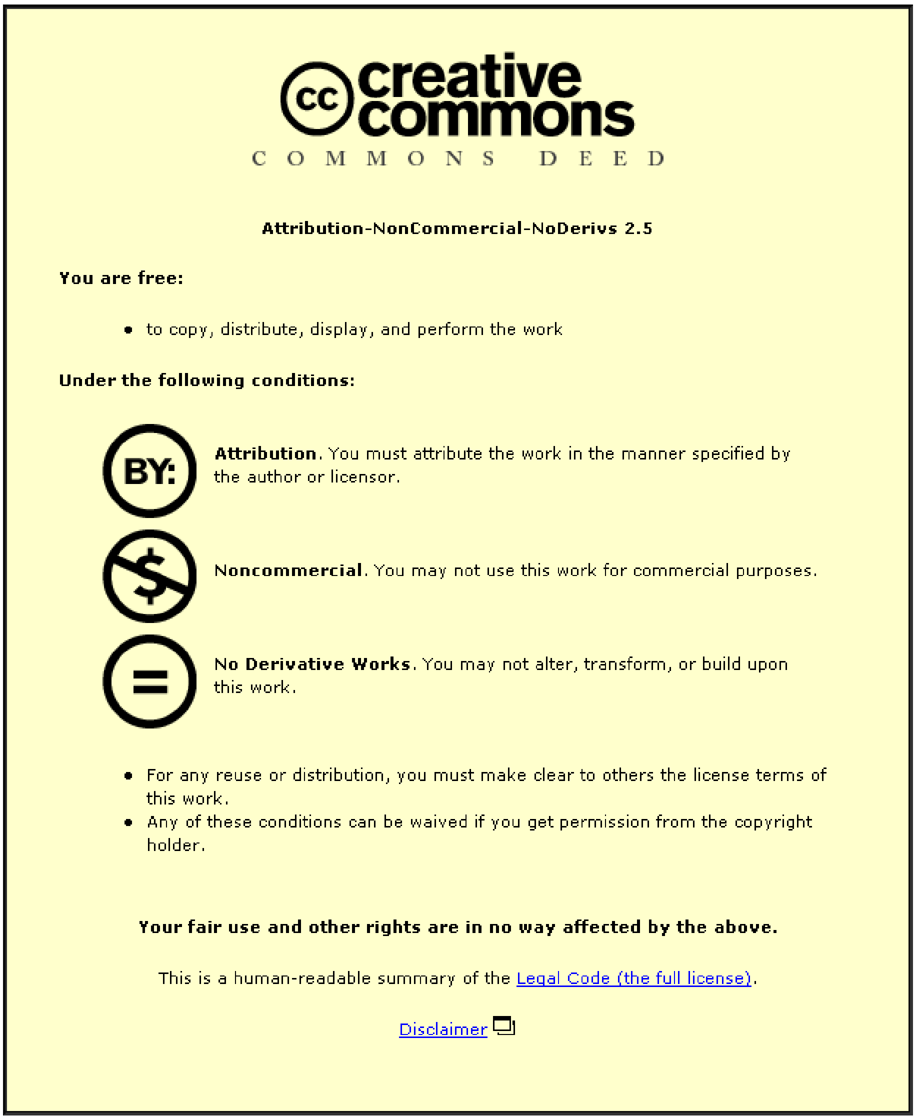

PRESSURE LEAF FILTER CONTROL AND THE PREDICTION OF PERFORMANCE

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ABSTRACT

The widespread reliance on heuristics for the design and specification of particle/fluid separation devices has prompted a new approach to pressure filtration which incorporates the principles of mechatronics. By combining accurate experimentation with classical filtration models it is shown how the performance of a deadend pressure leaf filter can be predicted over a range of process conditions. An experimental apparatus is described along with data which illustrate its versatility and accuracy. Experimental data obtained from the apparatus with aqueous mineral suspensions are shown to compare favourably with theoretical predictions of important design parameters such as cake height and cumulative volume of filtrate. Preliminary results from unique constant flow filtration experiments are also presented where the air pressure within the filter was controlled through a combination of flow & pressure transducers and an electronically adjusted pressure regulator. Their combination allowed filtrations performed under different pressure/flow regimes to be compared as identical suspension characteristics could be maintained.

KEYWORDS

Cake filtration; Mechatronics; Control; Simulation.

INTRODUCTION

For many years separations technologists have attempted to understand cake filter performance with varying degrees of success[1-8]. The fact that we are still heavily reliant on heuristics or 'rules-of-thumb' for the design and specification of such separation devices[9] indicates the difficulties which researchers have encountered in predicting the complex, transient behaviour of solid/liquid mixtures. Eliminating the need for heuristics would preclude the need to perform many costly experiments when specifying larger scale filters and save both time and financial investment. With the advent of mechatronics, technologists now have the opportunity to examine filtration processes in new, novel and more accurate ways and thus move towards removing heuristics from the design and specification of filters.

EXPERIMENTAL PHILOSOPHY

Cake filtration has attracted a great deal of academic interest for many years now due to its widespread use throughout the chemical and process industries. Whilst much of the research has undoubtedly progressed our understanding, the majority has utilised what must now be considered relatively elementary 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. Potentially variable operator interference has plagued filtration research over the years with the result that experimental data have often been unreliable and difficult to obtain quickly.

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The long standing need to develop more suitable apparatus can now be addressed through mechatronic principles. Here, the combination of mechanical design, electronics and computers leads to the generation of more reliable experimental data. The experimental apparatus used in this study has been described in detail previously[10,12]. Briefly, the fully automated and computer driven apparatus comprised of a stirred feed vessel and an 80 cm^2 deadend pressure leaf filter containing 256 electrode probes arranged in sixteen horizontal rings throughout the height of the filter cell. By switching electrode pairs through dedicated electronics the cake structure, cake saturation and cake height could be determined at any given time. All sequencing of the apparatus and data acquisition were performed by an attached personal computer in a consistent manner at test pressures up to 600 kPa.

One of the many novel features of the apparatus was an ability to perform filtrations over a range of different pressure/flow regimes without changing the inherent properties of the feed suspension. The pressures required to progress filtrations were provided by the combination of a dedicated compressor and an electronic pressure regulator. Adjustment of the regulator via computer, a suitable control algorithm and flow measurements allowed constant pressure, constant flow and (potentially) variable pressure/flow filtrations to be performed. Whilst constant pressure filtrations were relatively simple to implement, those filtrations requiring changes in pressure necessitated continual adjustments to an extent dependent on the nature of the feed suspension and the desired process conditions. Filtrate flows were monitored via successive timed readings from an electronic balance interfaced to the computer. The flow rate readings were interpreted by the control algorithm and the filtration pressure adjusted according to the controller settings and the current flow offset. Whilst several types of controller have been tried to date, the majority of work has concentrated on a negative feedback proportional controller with

$$\text{controller output} = K_p E \qquad (1)$$

where K_p is the proportional gain and E is the offset between the flow set point and the measured filtrate flow. 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.

The filtration data shown in Figures 1-8 were obtained using 0.2 µm rated Gelman Versapor™ membranes and aqueous mineral suspensions of calcite and talc. Characterisation tests showed calcite to have a 50% dispersed particle size of 11.3 µm, a ζ-potential of -20 mV @ pH = 10.5, a rhomboidal shape and a tendency to form relatively incompressible filter cakes. Conversely, talc exhibited a 50% dispersed particle size of 8.5 µm, a ζ-potential of -55 mV @ pH = 11.0, a platelet shape and a tendency to form moderately compressible filter cakes when filtered from aqueous suspension. The Versapor membranes had a measured 50% pore size of 0.25 µm, a measured hydraulic permeability of 7.0x10^{-15} m^2 and an average thickness equal to 185 µm.

EXPERIMENTAL RESULTS AND DISCUSSION

Figure 1 illustrates filtration data from six experiments using calcite suspensions where cake formations proceeded at constant pressures between 100 & 600 kPa. With the apparatus described it was possible to routinely perform such experiments in a repeatable manner, not just for nearly incompressible materials such as calcite, but also for materials forming more compressible cakes such as talc and zinc sulphide[11,13]. Using standard t/V vs. V plots, filtration data for calcite showed average specific cake resistance (α_{av}) values to range between 1.1x10^{10} and 1.5x10^{10} m kg^{-1} over the pressure range 100-600 kPa, with the calculated filter medium resistance (R_m) varying between 1.1x10^{10} and 2.0x10^{11} m^{-1}. Corresponding data for talc showed α_{av} to vary between 4.3x10^{10} and 1.9x10^{11} m kg^{-1} with R_m taking values between 3.8x10^{10} and 3.0x10^{11} m^{-1}. The more compressible nature of the talc system is evident from the span of α_{av} values and these, in combination with cake solids concentrations measured via the electrode probes inside the filter cell, where used to determine the four scale-up constants which characterise a filtration[13 †].

Figures 2 & 3 show more constant pressure filtration data for 10% v/v calcite and talc suspensions respectively. As expected, with the relatively incompressible calcite system a higher pressure (and feed concentration) formed a thicker cake in a given time; the measured cake concentrations were raised at higher pressures but varied only slightly during a given test. For more compressible systems such as talc a wider range of concentrations were typically seen through a filtering cake and these concentrations would increase markedly as filtration progressed. The accuracy of such data were confirmed by appropriate mass sampling and the form of a transient solids concentration profile gave a good indication of the cake compressibility and particle rearrangement induced by the flow of liquid through cake interstices.

Figure 4 shows example data where proportional control has been used to maintain an incompressible cake filtration at constant flow conditions with a set point of $5x10^{-7}$ m^3 s^{-1}. The behaviour is typical of proportional control whereby the overshoot response observed toward the start of filtration is followed by a decaying oscillatory response. The latter results in a near constant filtrate flow at a fixed offset of 15% from the set point. During the constant rate period the filtration pressure rises in an essentially linear manner in accordance with classical filtration theory[13] until the maximum allowed pressure is reached. At this point constant pressure filtration commences and the filtrate flow rate is seen to decay in the expected manner until the end of the test. It is clear from Figure 4, and other data[12], that with computer control the facility exists for constant pressure, constant flow and variable pressure/flow tests to be performed within one experimental apparatus. Suspensions can be introduced to a filter in a consistent manner and, through appropriate control of the delivery pressure and flow monitoring, filtrations performed to mimic pumping operations with both positive displacement and centrifugal pumps.

Figure 5 shows an example of how flow response altered in supposedly constant flow calcite filtrations as proportional gain was changed over the range $5x10^4$-$6x10^5$. At lower values of gain the response time was slow, the offset from the set point was relatively large and appropriate flow control was not established within the time constraints of the experiment. As the gain increased so the response time was reduced at the expense of a greater overshoot and more oscillations about the lower flow offset. At yet higher gains the flow response became unsatisfactory and sufficiently good control could not be established within the relatively small time frame available. Although such behaviour is to be expected from a proportional control algorithm, more work is required with both this and other forms of controller to find optimum controller settings and facilitate detailed comparisons between different modes of filtration.

Figures 6-8 give examples of experimental data and predictions made using classical filtration theories[11] for calcite suspensions. In Figure 6 constant pressure filtration data for calcite are shown to illustrate how cumulative volume of filtrate vs. time and cake height vs. time can be predicted with a degree of confidence when reliable scale-up constants are available. The excellence of the predictions are indicative of the accuracy of simulation[11] when incompressible systems which sediment at a relatively low rate are considered. The data in Figure 6 are particularly significant as the predictions were made using scale-up constants derived from the second filtration apparatus incorporating the filter cell with 32 electrodes. Similarly good predictions of filtrate volume could be obtained for constant pressure talc filtrations involving the formation of moderately compressible cakes. However, when appreciable settling of particulates accompanied filtration, such as with the separation of more dilute zinc sulphide suspensions, predicted values fell below those observed in experiments by up to 10%[14].

[†] Scale-up constants for calcite were also available from a second computer controlled apparatus which employed a filter cell of area 22.8 cm^2 and 32 pairs of electrodes arranged in a single vertical plane.

Figure 7 shows some comparisons between experimental and theoretical flow responses for constant flow calcite filtrations at two different set point flows. The theoretical predictions were made by iteratively solving combinations of equations derived from classical control theory (incorporating eqn. (1)) and classical filtration theory such that the relationship between filtration time (t_f) and filtration pressure (Δp) is given by

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

where e_{av} is the average cake voids ratio, A the filter area, μ the filtrate dynamic viscosity, M_s the solids mass fraction in the feed, ρ the filtrate density, ρ_s the solids density and Q the filtrate flow rate. The values of the four scale-up constants used to evaluate α_{av} and e_{av} in eqn. (2) were derived from constant pressure filtration data. For both experimental data sequences in Figure 7, the theoretical predictions of flow response are relatively good, particularly for flow offset and response time. The ability to predict filter performance by computer algorithm is of obvious benefit to the researcher and design engineer alike as is the ability to predict constant flow filtration performance from a knowledge of constant pressure filtration behaviour. In Figure 8 the two sets of constant flow filtration data displayed in Figure 7 are compared with predictions made from the classical filtration theory presented in eqn. (2). No control algorithm is included in this case as eqn. (2) is 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 both set point flows are reasonably close to the experimentally measured values. As the work is at a relatively early stage it is probably premature to draw any definitive conclusions from Figure 8, however, the potential benefits of the approach are clear.

Several researchers have, in the past, attempted to perform laboratory scale filtration experiments at conditions of constant flow and/or variable pressure/variable flow by utilising (a) positive displacement or centrifugal pumps[15,16], (b) the manual adjustment of pressure during filtration[17,18] or (c) a specially driven piston press[19]. Whilst each approach has yielded experimental data there are inherent problems which are difficult to reconcile with confidence. The approach taken in this paper utilises a single, fully automated, computer controlled, apparatus. This allows experiments to be performed in a repeatable manner to mimic the operation of industrial filtrations using positive displacement and centrifugal pumps. 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 sequences of essentially static experiments. 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 was shown how mechatronic principles can provide automated experiments for a range of filtration conditions and feed suspensions without changing the characteristics of feed. It has also been shown how flexible computer simulations can predict separation performance when constant pressure and constant flow regimes are used and 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 flows accurately over wide ranges in reliable and repeatable manners. With these in place it should prove possible to quantify filtration characteristics in better forms than the series' of static constant pressure tests currently used, thus allowing for more accurate scale-up methodologies and less reliance on heuristics.

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NOMENCLATURE

A	Filter area (m^2)
e_{av}	Average cake voids ratio
E	Flow offset ($m^3\ s^{-1}$)
K_p	Proportional gain
M_s	Solids mass fraction in the feed (kg/kg)
Q	Filtrate flow rate ($m^3\ s^{-1}$)
R_m	Filter medium resistance (m^{-1})
t_f	Filtration time (s)
V_f	Cumulative volume of filtrate (m^3)

α_{av}	Average specific cake resistance ($m\ kg^{-1}$)
Δp	Filtration pressure (Pa)
μ	Filtrate dynamic viscosity (Pa s)
ρ	Filtrate density ($kg\ m^{-3}$)
ρ_s	Solids density ($kg\ m^{-3}$)

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FIGURES AND TABLES

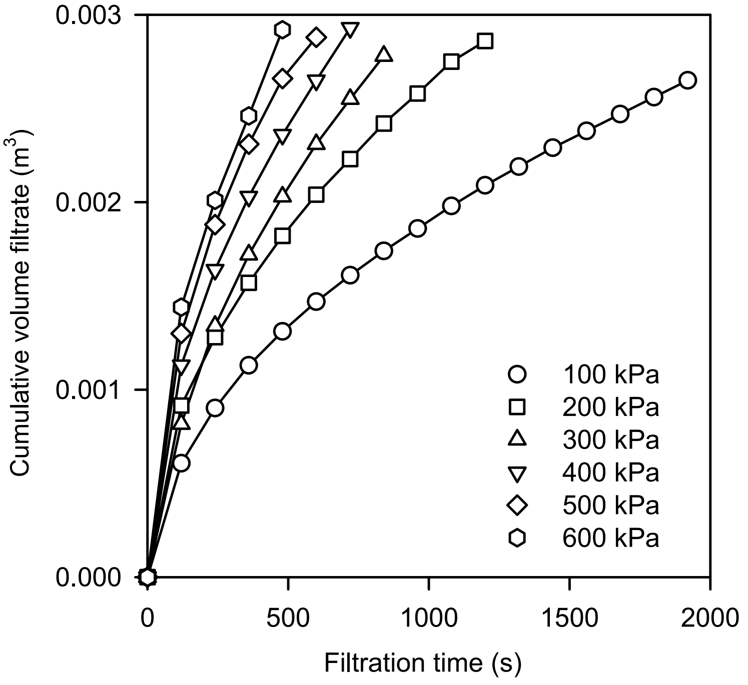

Figure 1: Filtration data sequences for 10% v/v calcite suspensions.

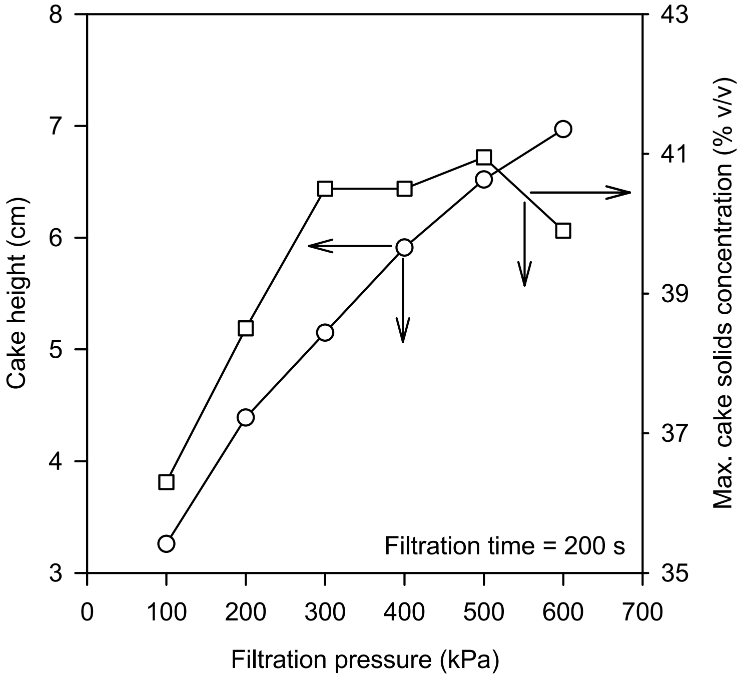

Figure 2: The effects of pressure on cake formation during the filtration of 10% v/v calcite suspensions.

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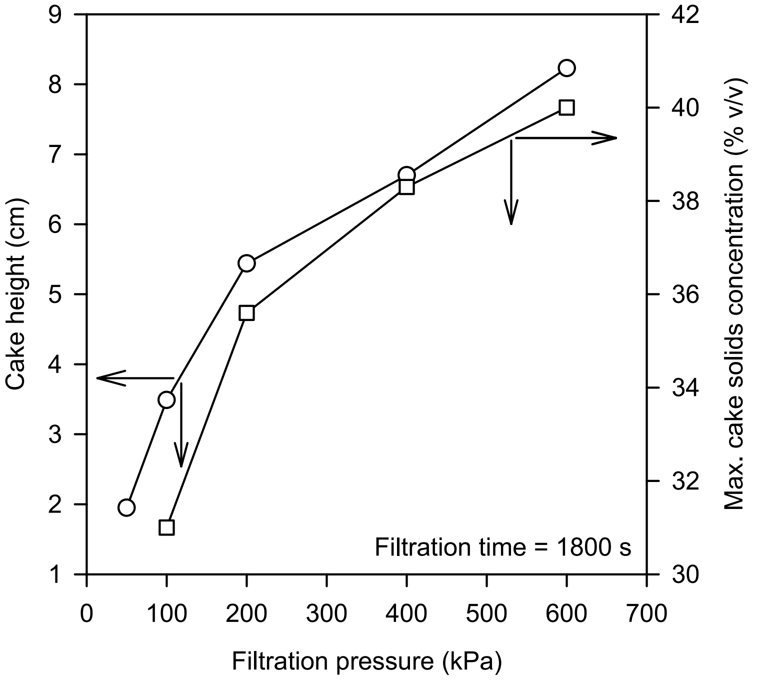

Figure 3: The effects of pressure on cake formation during the filtration of 10% v/v talc suspensions.

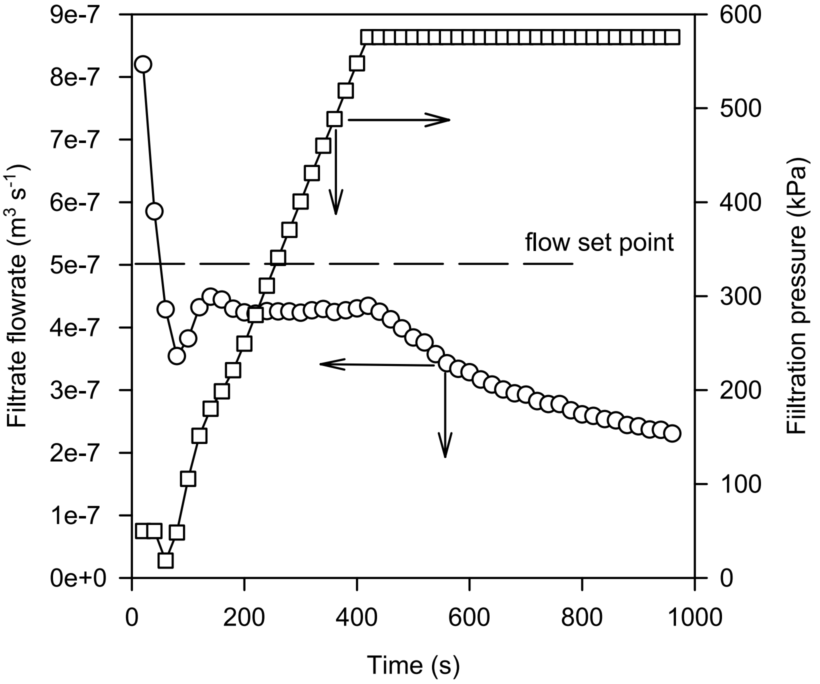

Figure 4: Typical pressure and filtrate flow rate histories for the proportionally controlled filtration of a suspension.

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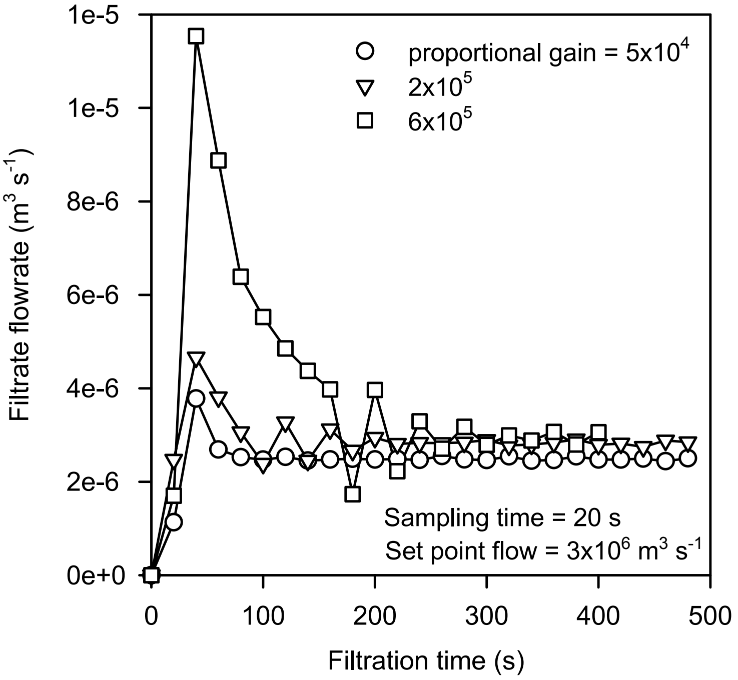

Figure 5: The effect of controller proportional gain on flow response for calcite suspensions.

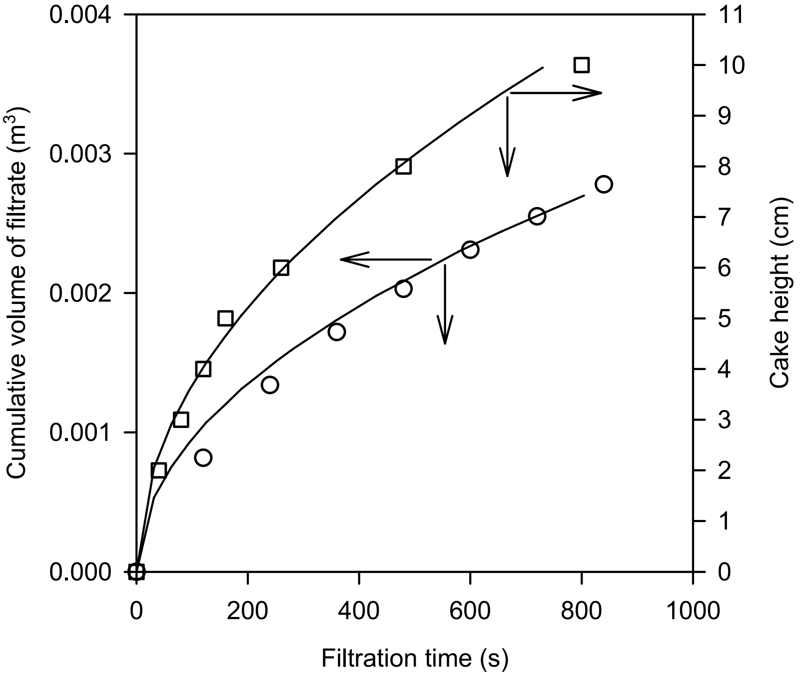

Figure 6: Comparisons of experimental and predicted data for calcite filtrations at constant pressures.

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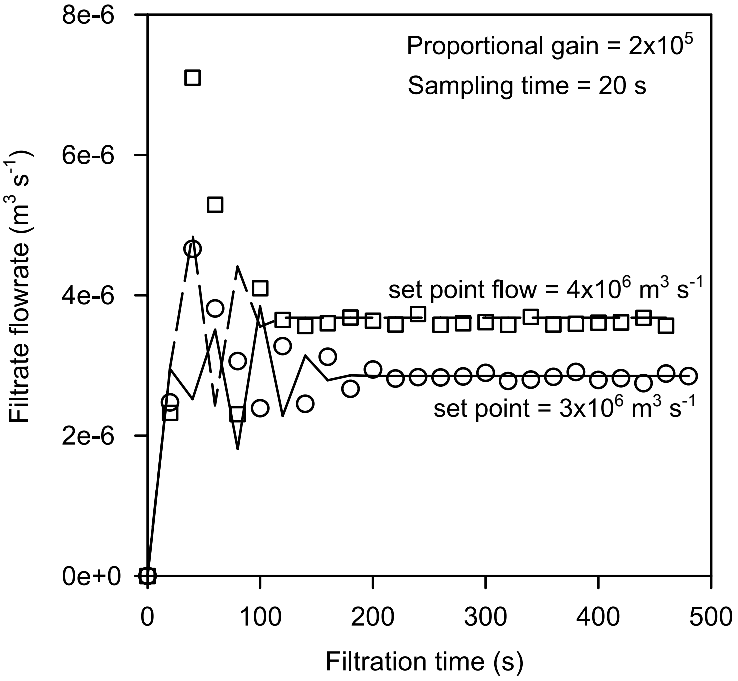

Figure 7: A comparison of experimental and theoretical flow histories for the constant flow filtrations of two calcite suspensions.

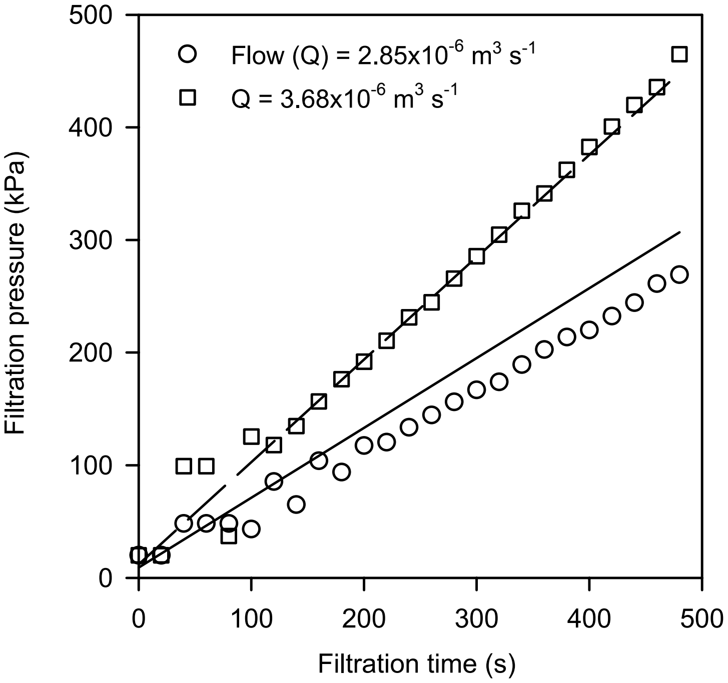

Figure 8: Comparisons of experimental calcite constant flow data and predictions made using classical filtration theory.

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