The control of pressure in constant rate cake filtration

THE CONTROL OF PRESSURE IN CONSTANT RATE CAKE FILTRATION

E.S. Tarleton (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 approach to pressure filtration incorporating the principles of mechatronics. A unique experimental apparatus is described and used to obtained filtration data for aqueous mineral suspensions forming either incompressible or moderately compressible filter cakes. Data for constant flow filtrations are presented where the air pressure within the filter is controlled through flow & pressure transducers and an electronically adjusted pressure regulator. Their combination allowed filtrations performed under different pressure/flow regimes to be compared. It is shown how scale-up data obtained from constant pressure filtrations can produce erroneous predictions of constant rate filtration behaviour, particularly as cake compressibility increases.

KEYWORDS

Cake filtration; Mechatronics; Control.

EXPERIMENTAL PHILOSOPHY

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.

The apparatus used in this study has been partly described in detail previously and allowed experiments to be performed routinely 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[1-4]. The fully automated and computer driven apparatus is shown schematically in Figure 1 and comprised of a stirred feed vessel and a dead-end pressure leaf filter cell of 80 cm^2 area. 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 both constant pressure and constant flow filtrations to be performed. Whilst constant pressure filtrations were relatively simple to implement, constant rate filtrations required continual pressure 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. For the purpose of the current investigation, the flow rate readings were interpreted by a proportional control algorithm and the filtration pressure adjusted according to the controller settings and the current flow offset.

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The filtration data shown in Figures 2-8 where obtained using 0.2 μm rated Gelman Versapor™ membranes and aqueous 10% v/v 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 7.0×10^{-15} m^2 and an average thickness of 185 μm.

EXPERIMENTAL RESULTS

Constant pressure experiments over the range 100-600 kPa were performed to determine the compression characteristics of calcite and talc filter cakes. Using standard t/V vs. V plots and consistent analysis procedures, filtration data for calcite showed average specific cake resistance (α_{av}) values to range between 1.1×10^{10} and 1.5×10^{10} m kg^{-1} with the calculated filter medium resistance (R_m) varying between 1.1×10^{10} and 2.0×10^{11} m^{-1}. Corresponding data for talc showed α_{av} to vary between 4.3×10^{10} and 1.9×10^{11} m kg^{-1} with R_m taking values between 3.8×10^{10} and 3.0×10^{11} m^{-1}. The more compressible nature of the talc system is evident from the wider span of α_{av} values and these, in combination with measured cake solids concentrations, were used to determine scale-up constants for both calcite and talc[3].

Figure 2 shows the typical form of flow response when a negative feedback proportional controller was employed to perform a constant rate filtration with a sampling time of 20 s. The initial overshoot flow response was followed by a decaying oscillatory response until the flow settled to within ±5% of the set point or ±5% of a ‘steady’, pseudo-equilibrium flow below the set point. During the initial oscillatory period the system pressure would vary according to the larger recorded deviations from the desired flow. After a period, typically between 40 and 150 s, the flow response would become more stable and the filtration pressure progressively increased in order to compensate for the growing cake. Where the maximum system pressure of 600 kPa was reached constant pressure filtration commenced and the filtrate flow rate decayed until the end of the experiment.

Ranges of constant flow filtrations with both calcite and talc suspensions indicated that the variables controller gain, set point flow, initial pressure and sampling time were important in determining adequate responses from the filtration apparatus (see Figure 3 and Tarleton[4]). Their influences may be summarised as follows:

- At lower values of gain the offset from the set point was relatively large and appropriate flow control could not be established. As gain was increased so response time remained essentially constant, however, a greater overshoot and more oscillations about the reduced offset flow were observed. At yet higher gains the flow response became unsatisfactory and sufficiently good control could not typically be obtained within the time constraints of an experiment.

- As the required set point flow was increased so the response time was generally reduced, however, this was at the expense of increased flow offset. The latter, 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. At lower set points both the flow and pressure responses tended to be more oscillatory to the extent that response times in excess of 300 s were commonly recorded with correspondingly poor control of cake formation.

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- In general terms a reduced sampling time provided for an improved response time. With a 5 s sampling time, flow control could be established within 20 s of the start of an experiment. For longer sampling times more oscillations were observed about the set point flow.

Figure 4 shows the flow and pressure responses for a proportionally controlled 'constant rate' calcite filtration with a set point flow of 6x10^{6} m^{3} s^{-1}, a proportional gain of 2x10^{5} and a sampling time of 20 s. The flow behaviour is similar to that shown in Figure 2 whereby the overshoot response observed toward the start of filtration is followed by a decaying oscillatory response. For the example data shown the flow settles after ~80 s to within ±5% of an essentially equilibrium flow which is ~19% below the desired flow set point. During the constant rate period (<320 s) the filtration pressure increased in an essentially linear manner with a typical regression coefficient for pressure (Δp) vs. time (t) being in excess of 0.99. This is in accordance with classical filtration theory which, for a suspension forming an incompressible cake, may be stated as

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

where t_f is the filtration time, e_{av} the average cake voids ratio, α_{av} the average specific cake resistance, 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, R_m the filter medium resistance and Q the filtrate flow rate. Talc suspensions, which tended to form more compressible cakes, produced filtration responses similar to Figure 5. Here, the greater compressibility of a forming cake dictated that the control of pressure, and hence flow, was generally more difficult. In some cases, such as in Figure 5, this lead to a slow progressive increase in flow offset. The latter observation is thought to be a facet of using a proportional controller. It would appear that proportional control is sometimes incapable of responding to the demands imposed by a growing, compressible filter cake, a situation which may potentially be eliminated by moving to other, more sophisticated, control algorithms. During the period of a typical test with talc the pressure response would exhibit some curvature as time proceeded, this being indicative of moderate cake compressibility. Classical theory for the constant rate filtration of a compressible system suggests that curvature should exist as

$$t_f = \frac{A^2\left(1 - M_s\left(1 + e_{av}\left(\rho/\rho_s\right)\right)\right)}{\mu\rho M_s Q^2 \alpha_0\left(1 - n\right)}\Delta p_c^{1-n} \qquad (2)$$

where Δp_c is the pressure gradient across the cake and α_0 and n are the scale-up constants relating to specific cake resistance.

It is clear from Figures 2-5, and other data[4], that with computer control the facility exists for constant pressure, constant flow and (potentially) 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.

DISCUSSION

The ability to predict filter performance 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.

The scale-up constants derived from series of constant pressure experiments and used in the calculation of α_{av} and e_{av}, can be incorporated in the general filtration equation to give

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

where V_f is cumulative volume of filtrate. Predictions of constant pressure filter performance can be made from eqn. (3) and typical data for moderately compressible talc filtrations are shown in Figure 6. The progressive changes with raised pressure are self evident and the data in Figure 6 again highlight the benefit of being able to perform experiments in an automated manner. The theoretical predictions of filtrate volume vs. time show good agreement with experimental values and compliment the equally good predictions for less compressible calcite filtrations[5].

Although some progress has recently been made in the field of computer simulation[6-8], it is still recommended practice for variable pressure filtration performance to be empirically predicted from a knowledge of constant pressure filtration behaviour[9]. Figures 7 & 8 illustrate how this procedure can be applied to predict the constant flow/variable pressure filtration of calcite and talc suspensions respectively. In Figure 7 the pressure responses are compared with predictions made from the classical filtration theory presented in eqn. (1) and known scale-up constant values[3]. The predicted changes in pressure with time for all set point flows are reasonably close to the experimentally measured values, with perhaps the data at the higher set point flows showing the greatest deviations. Here, the filtration pressures increase more rapidly and, although calcite forms cakes of relatively low compressibility, it is possible that particle rearrangements induced in the growing cake by the increasing pressure 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. Figure 8 illustrates such a scenario for talc filtrations as the linear relation between pressure & time (on logarithmic scales) suggested by eqn. (2) is not obtained. Instead, typical data exhibit a distinct curvature which suggests that a significant time is required for particles forming the cake to rearrange themselves into the pseudo-equilibrium state expected for the given pressure. Many filtration models assume or imply that the particle rearrangements occur very rapidly, if not instantaneously, during filter cake formation. Should this assumption be incorrect then some doubt must be cast on the ability of these models for predict filter performance. Moreover, the use of constant pressure data acquired under essentially ‘static’ conditions to predict variable pressure filtration performance must also be questioned. As more ‘dynamic’ conditions prevail with the latter it may be prove necessary to re-examine procedures for the scale-up of filtrations involving variable pressure.

As the work presented here is at a relatively early stage of development it is probably premature to draw too many 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 is shown how mechatronic principles can be

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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 separation performance can be predicted when constant pressure and constant flow regimes are used and reliable scale-up parameters are available. Comparisons of constant pressure and constant flow filtrations have been presented and these suggest that difficulties may exist in using data derived under one pressure regime to predict filter performance over other pressure regimes. In order to verify such postulations it will be necessary to further develop the combinations of hardware, software and control philosophies to manipulate pressures and/or flows accurately over wide ranges in reliable and repeatable manners. With these in place it should be possible to quantify filtration characteristics in better ways, thus allowing for more accurate scale-up methodologies and less reliance on heuristics.

ACKNOWLEDGEMENT

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NOTATION

A	Filtration area (m^2)
e	Voids ratio (-)
M_s	Solids mass fraction in feed (kg/kg)
n	Compressibility index (-)
Q	Filtrate flow rate or set point flow (m^3 s^{-1})
R_m	Filter medium resistance (m^{-1})
t	Time (s)
V	Cumulative volume (m^3)

Greek symbols

α	Specific cake resistance (m kg^{-1})
α_0	Specific cake resistance at unit applied pressure (m kg^{-1})
Δp	Applied pressure (Pa)
μ	Filtrate dynamic viscosity (Pa s)
ρ	Filtrate density (kg m^{-3})
ρ_s	Solids density (kg m^{-3})

Superscripts and subscripts

c	cake
f	filtration phase
av	average value

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FIGURES AND TABLES

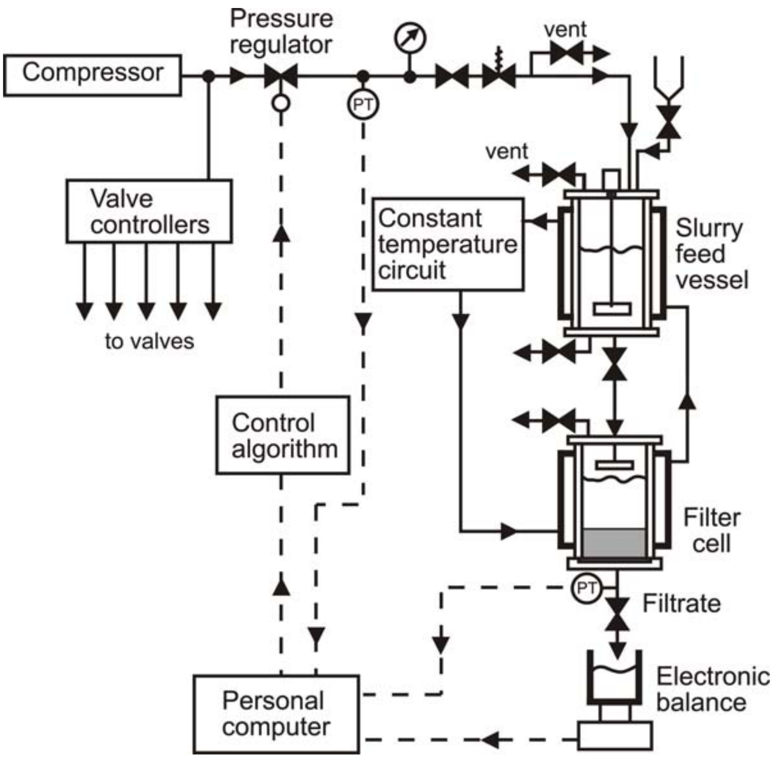

Figure 1: Schematic diagram of the filtration apparatus.

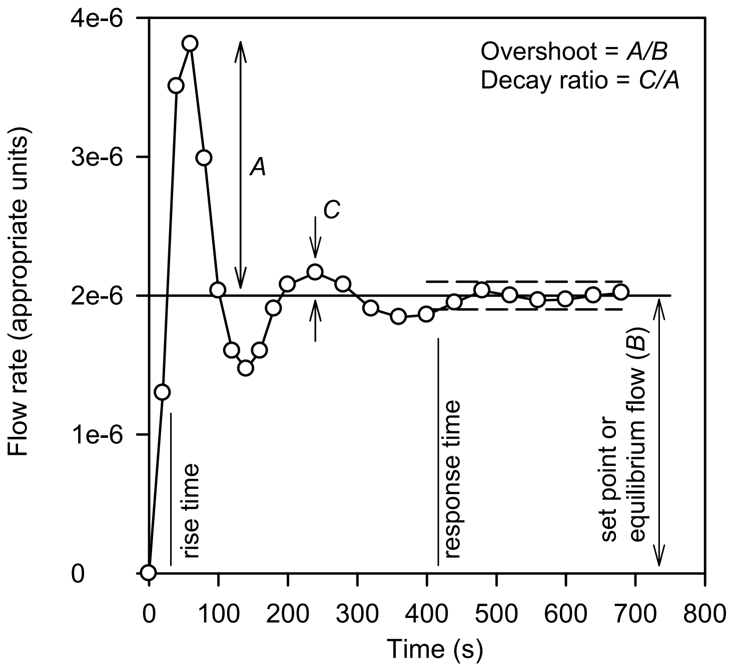

Figure 2: Typical flow response for a negative feedback, proportionally controlled filtration.

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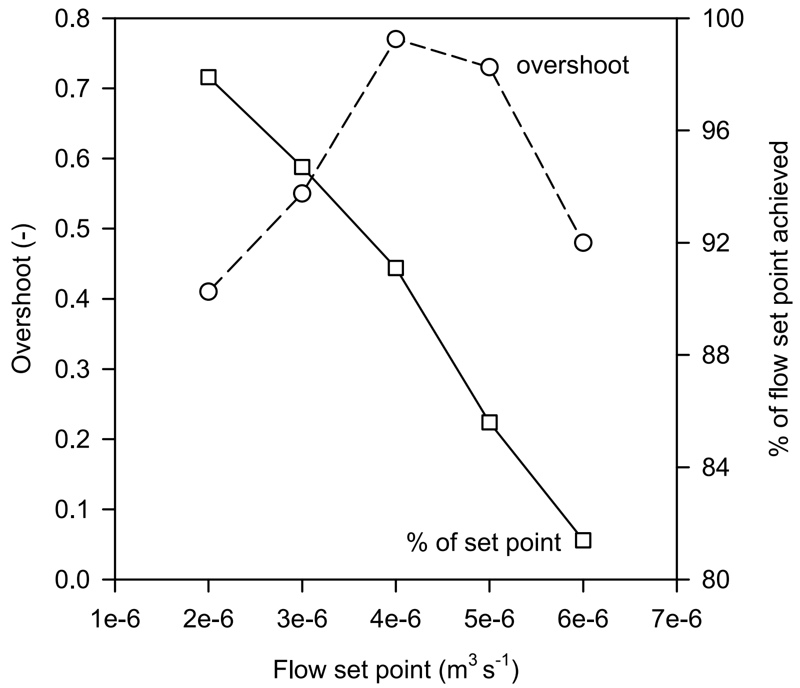

Figure 3: Typical influences of flow setpoint on controller responses.

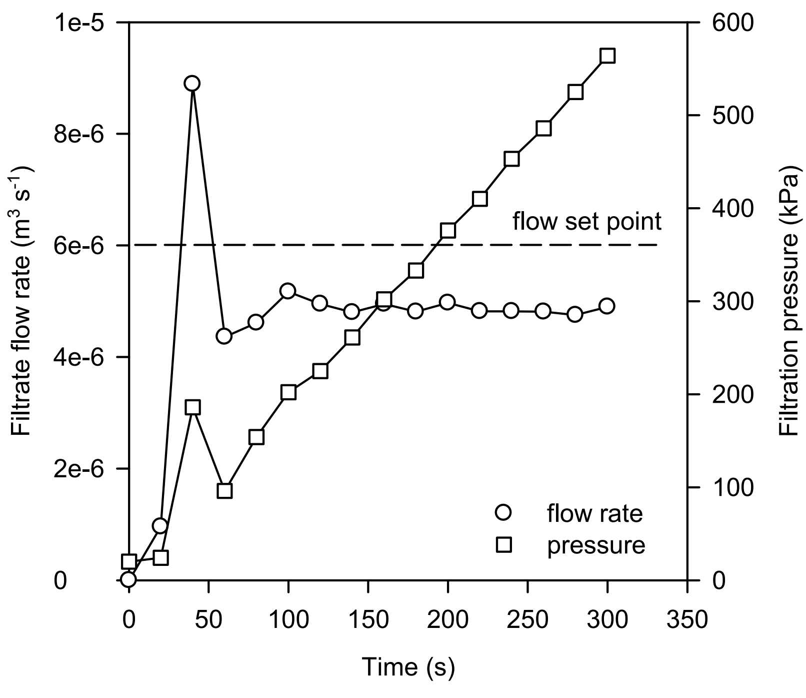

Figure 4: Pressure and filtrate flow histories for the proportionally controlled, constant rate filtration of a calcite suspension.

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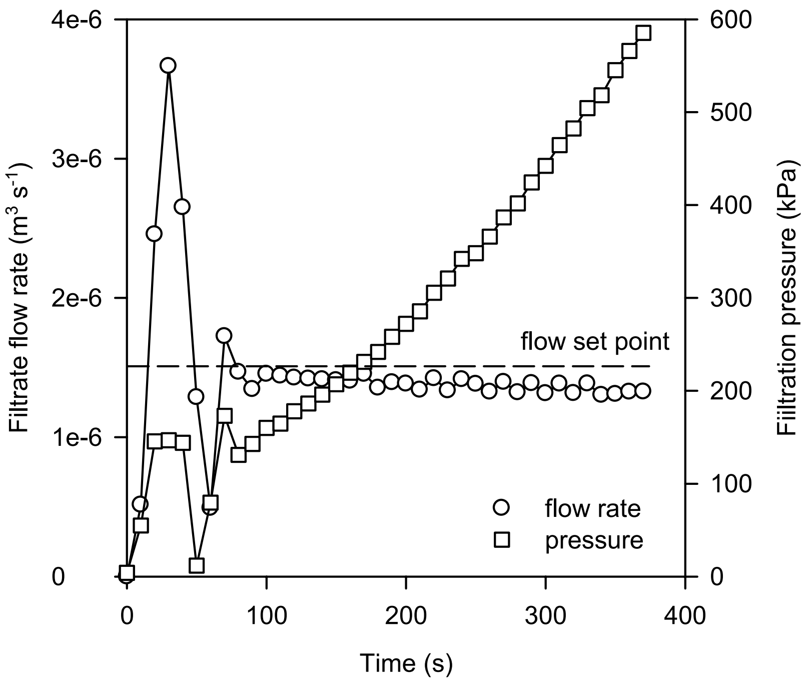

Figure 5: Pressure and filtrate flow histories for the proportionally controlled, constant rate filtration of a talc suspension.

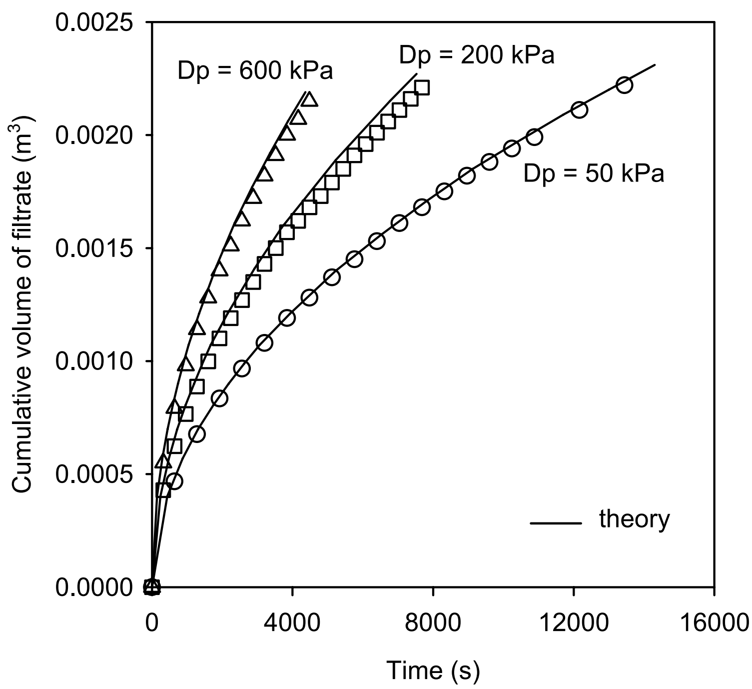

Figure 6: Predictions of *V* vs. *t* for the constant pressure filtration of talc suspensions.

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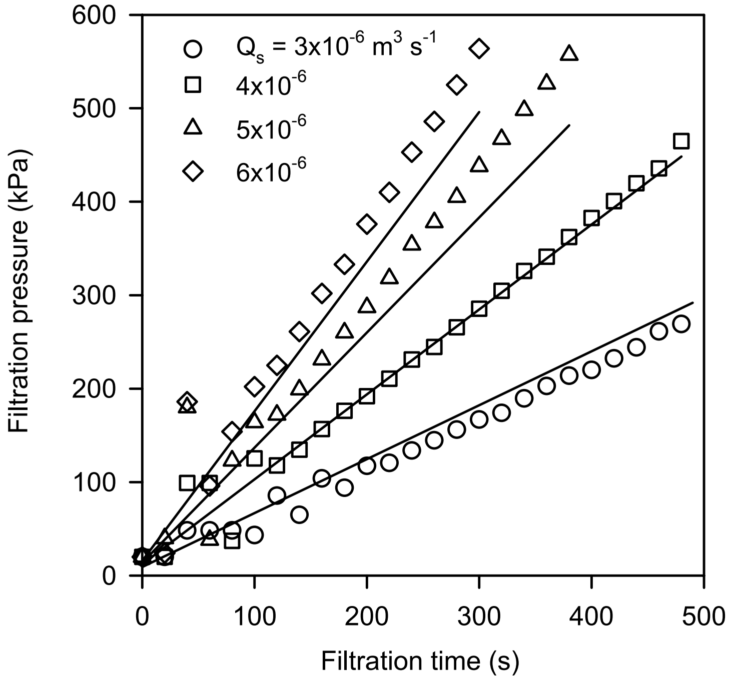

Figure 7: Comparisons of experimental constant flow calcite data and predictions made using classical filtration theory.

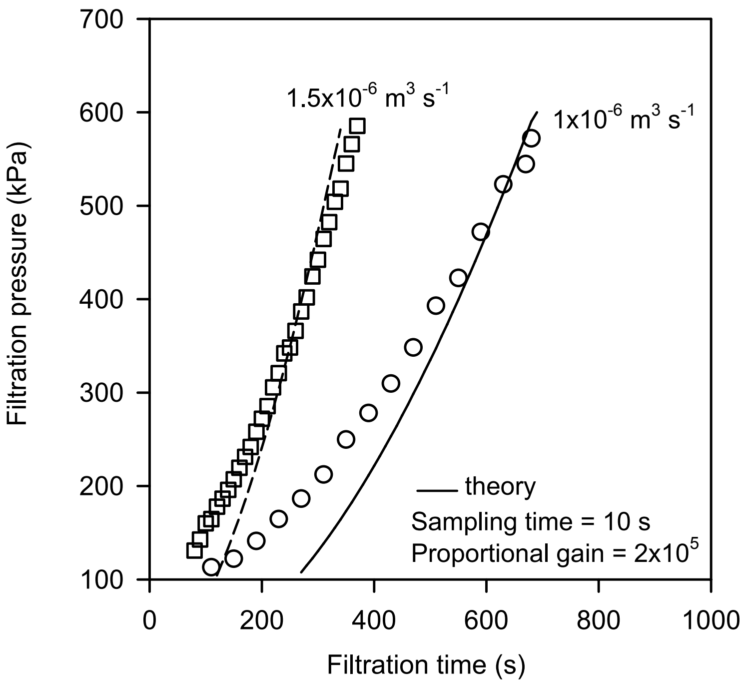

Figure 8: Comparisons of experimental constant flow talc data and predictions made using classical filtration theory.

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