FILTRATION

ISSN 1479-0602

the international journal for filtration and separation



The FILTRATION Society

AFS AMERICAN FILTRATION & SEPARATIONS SOCIETY

FILTRATION is the official journal of The Filtration Society and the American Filtration & Separations Society

NOTES FOR AUTHORS OF TECHNICAL PAPERS

Submission of Papers

1. Papers can be submitted to the Filtration journal in Word format via e-mail to the editor. Please include author(s) names and a correspondence address. Papers from industry and universities are equally welcome.
2. Papers must be in English and are normally up to 2500 words, but can be longer if necessary. The inclusion of appropriate, good quality, figures and tables is encouraged (and preferred).
3. There is no fixed format for a paper, but authors are asked to note the following:
   - Include an Abstract (up to 200 words) toward the start of the paper which gives a brief account of the most relevant aspects.
   - Provide a Conclusions section toward the end of the paper.
   - Any mathematical expressions should be typed and checked carefully for accuracy. Where several equations appear, a list of symbols used should be inserted at the end of the paper (before any References). SI units should always be used.
   - References should be listed in the order in which they are first cited in the text, where they are indicated by the superscript numbers. They should give in order: Author's surnames and initials, Year, Title of paper/chapter, Title of book or journal, Volume, Issue, Page number, followed by the name and town of the publisher in the case of a book.

Editorial Policy and Standards

1. Published papers are original contributions in the broad field of filtration, separation, clarification, dust control and related processes.
2. The Filtration journal is the official journal of The Filtration Society, The American Filtration & Separations Society and several other filtration societies around the world. The journal is distributed to Individual and Corporate Members of these societies on a quarterly basis.
3. The content of papers is professionally reviewed prior to publication. All published papers are considered for The Filtration Society's Gold Medal and Suttle Awards.
4. The Filtration journal is indexed and abstracted by Chemical Abstracts, GEOBASE, MEI Online and Scopus.
5. There is no charge for publishing a paper in the Filtration journal. However, if authors require figures to appear in colour they will be asked to pay a colour reproduction charge.
6. Upon publication a PDF of the published paper is sent (free of charge) to the corresponding author.

FILTER CAKE FORMATION WITH SIMULTANEOUS FILTRATION AND SEDIMENTATION

E.S. Tarleton (e.s.tarleton@lboro.ac.uk, www.stevetarleton.com)
Department of Chemical Engineering, Loughborough University, Loughborough, LE11 3TU, UK.

Data for near incompressible cake formations with simultaneous settling are presented. Aqueous calcite suspensions exhibiting similar median particle size, but different size distributions, were filtered over a range of constant pressures. For each experiment the time dependent history of filtrate removal and the particle size distributions of cake samples at different spatial positions were measured. These data were compared with predictions from a mathematical model that divides cake formation into a range of discrete time steps. Cake growth due to filtration and sedimentation were considered to proceed simultaneously, but separately, with the additive results predicting the change in cake thickness during a time step. Account was taken of the changing effects of suspension concentration on settling rate and the transient influence of size distribution on specific cake resistance.

The model is shown to quantitatively predict the influence of feed particle size distribution on cake formation and filtrate removal rates and favourable comparisons are made with values recorded in experiments. For the experimental conditions investigated, sedimentation is shown to contribute up to one third of the cake resistance in a filtration test. At lower pressures and with wider size distributions, larger particles from the feed tended to accumulate near the filter medium and in some cases a minimum cake resistance was observed toward a mean cake height. For higher pressures, however, the effect of particle sedimentation in filtration was reduced and cakes formed with near uniform median size through the cake height.

INTRODUCTION

Sedimentation of particles during deadend filtration can contribute to cake formation as well as the rate at which filtrate is extracted. Several researchers have previously investigated the phenomenon through a combination of experiment and theory[1-9] and concluded that the extent of influence is dependent on filter orientation, the properties of the feed mixture and, to a lesser degree, the septum characteristics. In several instances the literature is contradictory.

Most authors agree that sedimentation in downward filtration, with the filter surface uppermost, leads to a reduced filtrate flow rate due to additional cake formation. Some, however, suggest an (initial) preferential settling of larger particles to the filter surface, resulting in a lower local cake resistance (α) and a tendency towards increased filtrate flow and less medium blinding. For upward filtration, with the filter surface facing downwards, several authors note a greatly increased filtration rate due to particle settling away from the medium. Here, the potential flow rate gains from a reduction in the effective feed concentration (c) exceed the detrimental tendency to form higher resistant cake layers composed of finer particles. Conversely, several authors have noted how filtration rate can significantly fall in comparison to that recorded for downward filtration due to the preferential settling of larger particles away from the medium. Here, the remaining smaller particles near to the filter medium can result in medium blinding and/or the formation of thinner cakes of higher resistance during filtration.

It seems that the contradictory nature of the research literature may be due to different facets of the same phenomenon and a result of the combative influences of α and c on filter cake formation. If a cake can be thought to form as a sequence of layers, then the relative influences of α and c will control cake growth and thus filtration rate. Noting these concepts, this paper presents some results that attempt to quantify the effects of sedimentation in downward, incompressible, deadend filtration. Experimental data are compared with predictions from a model that divides the filter cell/feed suspension into a number of individual layers and treats filtration and sedimentation as separate, but additive, processes.

EXPERIMENTAL PROCEDURES AND CHARACTERISATION

The apparatus used in the filtration experiments is shown in Figure 1. All filtrations were performed in the downward direction with 5% w/w suspensions of calcite dispersed in double distilled water to yield clear filtrates.

In a test the (78.5 cm^2 area) stainless steel filter cell was initially filled with suspension. After a minimum, but fixed time delay, the filtration pressure was set to a constant value within the range 25-300 kPa and the filtrate valve opened to begin an experiment. Cake formation proceeded with the cumulative volume of filtrate being recorded as a function of time until the suspension within the cell was just exhausted. The filter cell was subsequently separated and samples of filter cake where taken to establish porosity by loss of weight on drying. Further samples of cake were taken

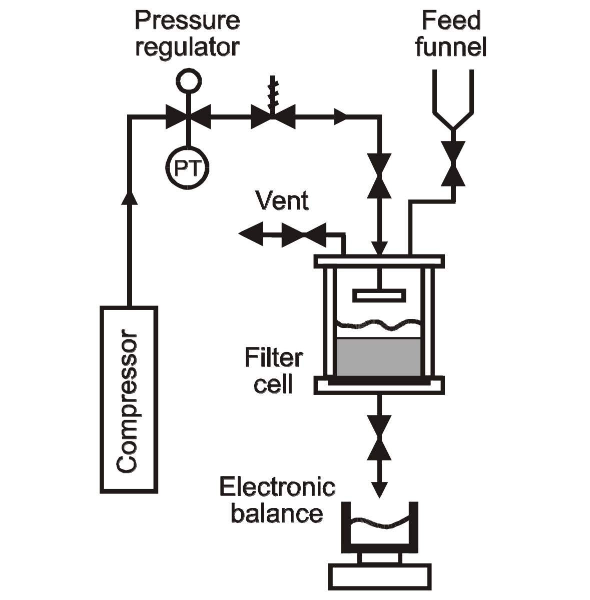

Figure 1: Schematic of the deadend filtration apparatus.

in an attempt to quantify any spatial variations in particle size distribution with distance above the septum. It was generally difficult to take representative samples from the relatively thin filter cakes formed (<25 mm) and most experiments were restricted to up to three size measurements through the cake height. Typical data showing aspects of experimental repeatability are given in Figures 2 and 3 and these, as well as subsequent results, confirmed the near incompressible nature of the calcite system previously observed[10,11].

The filter medium was Primapor, a polyurethane coated cloth supported by a 2:1 twill weave substrate. The medium had an overall thickness of 1.3 mm, a mean flow pore size of 4.3 μm as measured by Coulter Porometer and a permeability of 2.7×10^{-13} m^2 as measured by water permeation.

The size and size distributions of the filter cake samples and challenge suspensions were determined using a Malvern MasterSizer laser light scattering instrument; the results are summarised in Table 1. Two different batches of calcite solids were used and in their unground states the rhomboidal shaped particles exhibited median sizes of 11.7 μm and 9.6 μm respectively and relatively wide size distributions when dispersed. Suspensions with different median sizes were produced by wet grinding in a ball mill and over the period of 72 h a median size of 2.7 μm could be produced (e.g. grind 4). In some cases, two individual size distributions were mixed in appropriate proportions to give a, different size distribution, bimodal suspension of similar median size to one of the wet grinds (e.g. compare mix 1 with grind 1).

MODELLING

The modelling of filtration with simultaneous sedimentation was based on a previously proposed concept[4,12] and adapted suitably. The filter cell/suspension was vertically divided into (typically) 100 layers as shown in Figure 4 and the previously measured particle size distribution of the feed suspension divided into between 25 and 45 size classes of known frequency.

At t = 0 s the solids concentration in each layer is equal to the feed concentration (c_0) with size distribution (d) and thus the number, size and starting position of all the particles in each layer is known. For a time interval, Δt, between t = 0 and t_{max} s, it is considered

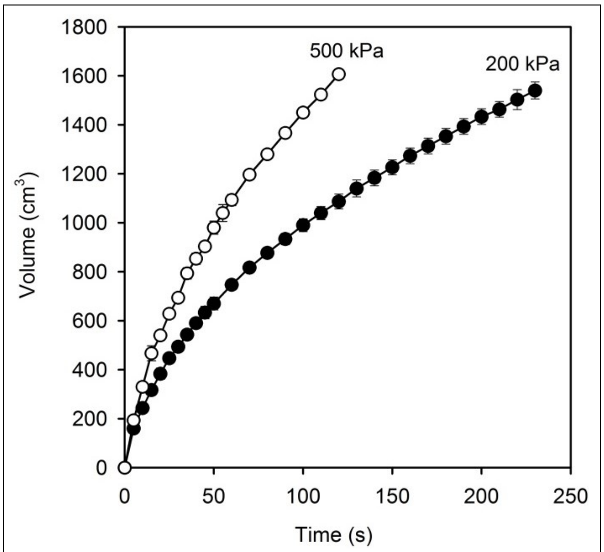

Figure 2: Typical variations between repeat filtration tests; Feed is 'unground 2'.

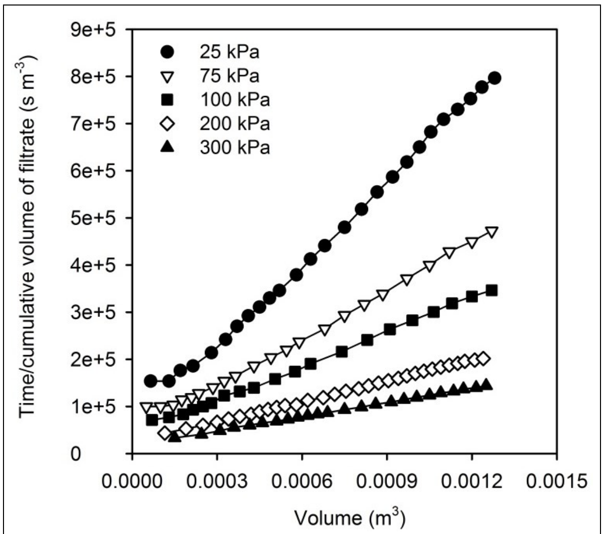

Figure 3: Sequential variation of experimental data with filtration pressure; Feed is 'grind 1'.

Suspension pretreatment	Designated name	10 % size (µm)	50 % size (µm)	90 % size (µm)
none	unground 1	2.42	11.66	26.10
wet grind 1.5 h	grind 1	0.84	7.47	14.03
wet grind 48 h	grind 2	0.62	4.22	6.74
unground 1 + grind 2	mix 1	0.85	7.65	21.89
none	unground 2	0.40	9.55	28.26
wet grind 6 h	grind 3	0.36	6.28	14.37
wet grind 72 h	grind 4	0.20	2.65	6.44
unground 2 + grind 4	mix 2	0.36	6.35	24.06

Table 1: Particle size data for the calcite suspensions.

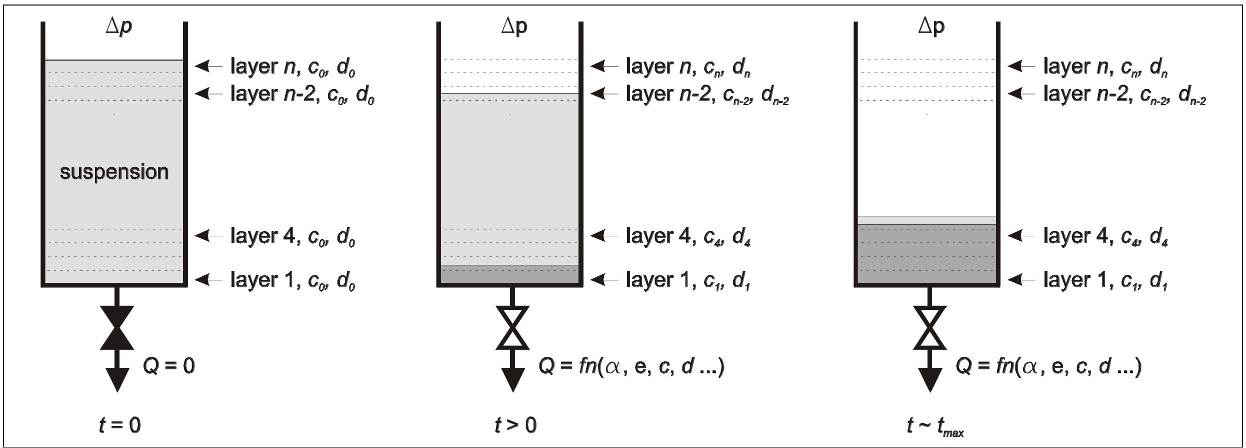

Figure 4: Schematic of the model for filtration with simultaneous sedimentation.

that filtration and sedimentation can be treated independently with the contributions to cake formation from each process being subsequently additive to give the overall filtration performance within the time interval.

For cake formation via sedimentation, particles within a layer are assumed to travel a distance (x_s) as given by the Richardson-Zaki correction to the Stokes equation:

$$x_s = \Delta t \frac{d_p^2 g(\rho_s - \rho_l)}{18\mu}(1 - V_s)^{4.65} \qquad (1)$$

where d_p is the diameter of a particle, g is acceleration due to gravity, ρ_s and ρ_l are the solid and liquid densities, respectively, μ is liquid viscosity and V_s is volume solids concentration. Particles of different diameter settle differentially as appropriate to new layers and those travelling sufficiently far to contact either the filter medium at the bottom of layer 1 (in time interval 1) or the top of the cake become fresh cake whose additional thickness (Δh_s) is:

$$\Delta h_s = \frac{V_{sc}(1+e)}{A} \qquad (2)$$

where e is the cake voids ratio, A is filter area and V_{sc} is particle volume joining the cake in Δt s.

For cake formation via filtration, the mass solids concentration (s_{chal}) and median size of the particles ($(d_{p,50})_{chal}$) challenging either the filter medium (in time interval 1) or the existing cake is determined. As the number and size of particles within each layer is known, the median of the distribution can be calculated and the challenge solids concentration is given by:

$$s_{chal} = \frac{(V_{sl}/V_l)\rho_s}{(V_{sl}/V_l)(\rho_s - \rho_l) + \rho_l} \qquad (3)$$

where V_{sl} is the volume of particles in a layer and V_l is total volume of a layer. The average specific resistance of the cake generated by freshly joining particles ($\alpha_{av.chal}$) is assumed to be given by:

$$\alpha_{av,chal} = (\alpha_{av,chal})_{t=0}\left(\frac{(d_{p,50})^2_{t=0}}{(d_{p,50})^2_{chal}}\right) \tag{4}$$

and the effective feed concentration (c) is a function of s_{chal}. The use of equation (4) involves an inevitable approximation to $\alpha_{av.chal}$. However, the closeness of the subsequently obtained model predictions to the experimental data supported the approximation and facilitated use of the model.

The volume of filtrate generated during the time interval Δt (i.e. ΔV) is given by iteration of equation (5), which is a form of the general filtration equation, such that the RHS of the expression has a value equal to Δt such that:

$$\Delta t = \Delta V\left(\underbrace{\frac{\mu R}{A\Delta p}}_{\text{medium}} + \underbrace{\frac{\mu\alpha_{av,chal}c_{chal}\Delta V}{2A^2\Delta P}}_{\text{new cake}} + \underbrace{\frac{\mu}{A^2\Delta P}B}_{\text{existing cake}}\right) \tag{5}$$

$$B = \sum_{n=0}^{n=t-\Delta t}\left((\alpha_{av,chal})_n(c_{chal})_n(\Delta V)_n\left(1+\frac{(\Delta h_s)_n}{(\Delta h_f)_n}\right)\right)$$

where R is the filter medium resistance, Δp is filtration pressure and the additional cake thickness due to filtration alone (Δh_f) can be calculated by:

$$\Delta h_f = \frac{\Delta V(1+e)}{A\left(\frac{\rho_s}{\rho_l}\left(\frac{1}{s_{chal}}-1\right)-e\right)} \tag{6}$$

The total added cake thickness is Δh_s + Δh_f and the new positions of particles within the filter cell after Δt are determined as x_s is known and all particles are assumed to translate vertically downwards by an amount proportional to the amount of extracted filtrate where $x_f = \Delta V/A$.

In the above manner and for a given set of process conditions and suspensions properties, calculations proceed to give a predicted time vs. filtrate flow rate data sequence and the particle size distributions throughout the cake height. In a typical simulation the error in the solids mass balance was <0.5%.

RESULTS AND DISCUSSION

Typical experimental data for the downward filtration of a range of suspensions are shown in Figure 5. It is clear that, as expected, with a raised filtration pressure the filtration rate also increased. For a fixed pressure, however, a suspension made from a mix of two size distributions (e.g. mix 1) always produced less filtrate than an equivalent test with a suspension produced from a single wet grind (e.g. grind 1). This phenomenon was confirmed through the calculated average specific cake resistances (α_{av}) and porosities (ε_{av}) where at 100 kPa, for example, α_{av} = 2.1x10^{10} m kg^{-1} and ε_{av} = 0.68 for grind 1 and α_{av} = 3.3x10^{10} m kg^{-1} and ε_{av} = 0.67 for mix 1. These findings were mirrored by corresponding experiments with 'grind 3' and 'mix 2' suspensions where the calculated differences in α_{av} between otherwise identical tests could (in extreme instances) approach an order of magnitude.

Figure 5 also includes model predictions of filtration performance. In the examples shown the model predicted the experimental data well and these were confirmed with similarly good predictions for the other available filtration V vs. t data. To use the model it was necessary to assume a specific cake resistance due to the first particles deposited on the filter medium (designated $(\alpha_{av,chal})_{t=0}$). As $\alpha_{av.chal}$ varied in a manner calculable by equation (4), the simulations facilitated a measure of the contribution to overall cake resistance by sedimented particles and Figure 6 shows examples of the results obtained and these reflect some of the conditions in Figure 5.

By comparing data for grind 1 with mix 1, and data for grind 3 with mix 2, it is evident that as the filtration pressure was raised (the filtration rate consequently increased) and the contribution to cake resistance due to sedimentation reduced. The results are also intuitive, as a raised pressure means less time being available for particles to sediment before the filtration is complete. In all cases the predicted influence of sedimentation is greater for suspensions prepared from mixes of two size distributions, presumably due to the greater proportion of larger particles in the feed (see Table 1). With 'grind 3' suspensions the contribution of sedimentation to cake formation was predicted as negligible by the model and this was confirmed by the ex-

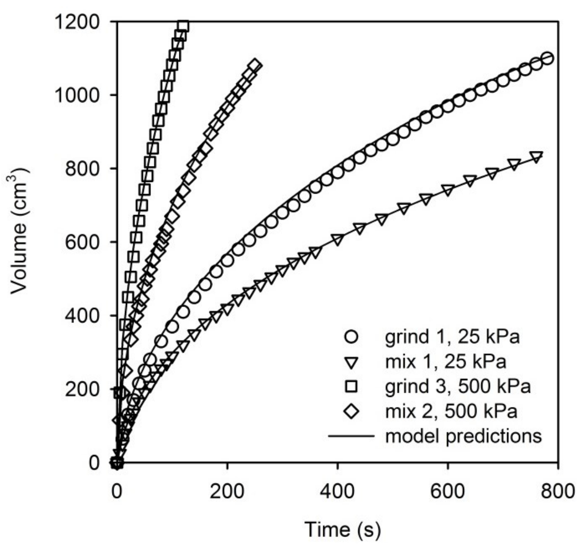

Figure 5: The effects of particle size distribution on filtration performance.

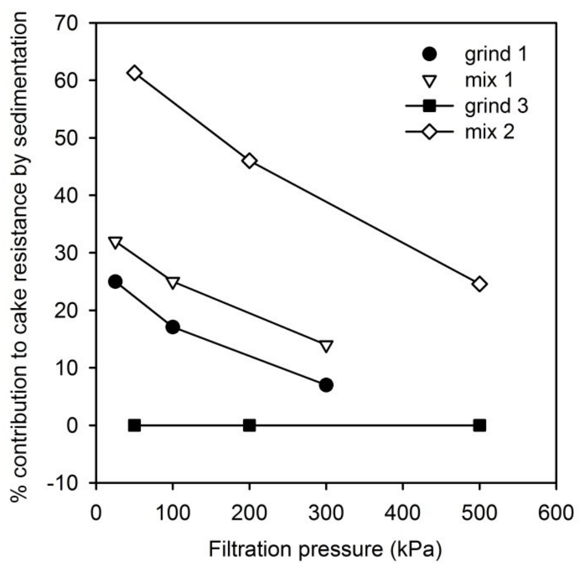

Figure 6: Predicted contributions of particle sedimentation to cake resistance as a function of filtration pressure.

perimental measurements described below.

Experimental measurements and theoretical predictions of particle size within filter cakes are shown in Figures 7-10.

Comparisons of Figures 7 and 8 show reasonable agreement between experiment and theory, although the experimental difficulties associated with taking representative samples of filter cakes inevitably contributes to some of the apparent differences. At the 100 kPa pressure represented by Figure 7, both the experimental data and the theoretical prediction suggest that the median particle size in the cake increases marginally with cake height. For corresponding experimental conditions in Figure 8 and a feed composed of the mix of two individual size distributions, both the experiment and model indicate a larger particle size toward the bottom of the filter cake adjacent to the medium and a similarly reduced particle size toward the top. These conditions arise as a consequence of particle sedimentation toward the filter medium. However, the model also predicts a maximum median particle size some way up the cake height with this corresponding to a minimum in the local cake resistance. Some authors[4,6] have previously reported results that support such a prediction and attribute the phenomenon to the differential settling of different particle size classes as well as the changing concentration of particles that challenge the cake surface with time.

Figures 9 and 10 show the experimentally measured effects of filtration pressure on the particle size distribution within filter cakes. With the suspension designated ‘grind 3’ and a filtration pressure of 50 kPa, the cake formed through its height with an almost constant median particle size close to the median size of the feed suspension. Raising the pressure had little effect as the measured particle size changed by a negligible amount. For the suspension designated ‘mix 2’, which comprised a mix of the two size distributions ‘unground 2’ and ‘grind 4’, the observed effects of filtration pressure are more marked. For the given experimental conditions and the lower pressure of 50 kPa, there was a sufficiently long time available for larger particles to sediment and result in a larger median size toward the bottom of the cake. At the higher pressure of 500 kPa

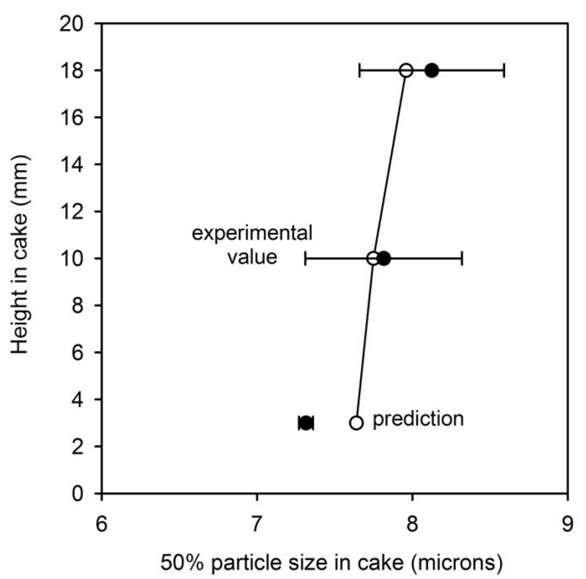

Figure 7: Experimental and theoretical particle sizes in a filter cake; Feed is ‘grind 1’, Δp = 100 kPa.

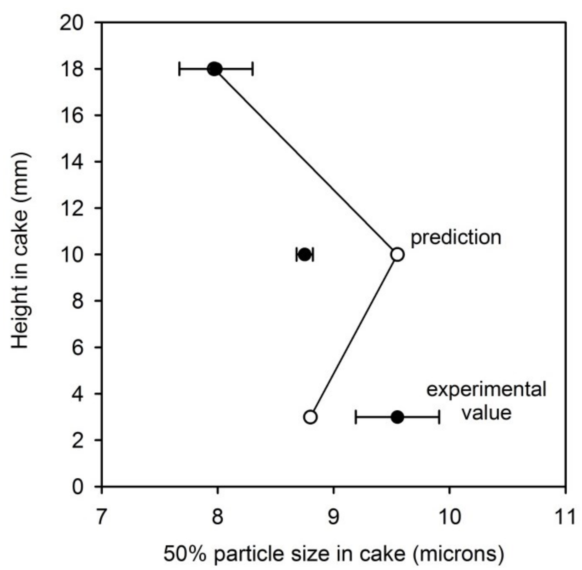

Figure 8: Experimental and theoretical particle sizes in a filter cake; Feed is ‘mix 1’, Δp = 100 kPa.

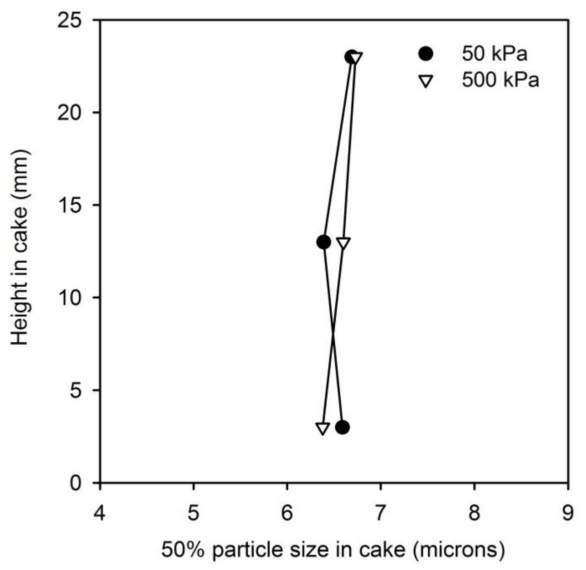

Figure 9: The effects of filtration pressure on the measured particle size in a filter cake; Feed is 'grind 3'.

the time available for sedimentation during the filtration was much reduced and the contribution to cake resistance from particle sedimentation was significantly lowered. Here, cake formed with near constant median size through the cake height that was again close to the median size of the feed. These findings confirm the data presented in Figure 6.

CONCLUSIONS

The work presented in this paper quantifies some of the effects of particle sedimentation that can occur during deadend filtration. It is evident that sedimentation may contribute a significant proportion of the cake resistance that is present during downward filtration and that the influence is reduced as the:

- filtration pressure/rate increases
- size of particles in the feed becomes smaller
- distribution of the feed becomes narrower.

Whilst the 'layer' model has been shown to predict filtration performance and particle size distributions in downward filtration, the author believes that the approach can be adapted and used to investigate other aspects of filtration. The influence of filter orientation is of obvious interest. However, examination of cake formations over different pressure and flow regimes are equally as important as is the extension of the model to include the compression of already formed cake layers. The latter is potentially difficult, although fundamentally necessary to provide a more complete understanding of cake filtration.

NOMENCLATURE

A	filter area (m^2)
B	variable that accounts for existing cake
c	effective feed concentration (kg m^{-3})
c_0	initial feed concentration (kg m^{-3})
d	representative of a particle size distribution
d_p	particle diameter (m)
$d_{p,50}$	median particle diameter (m)
e	cake voids ratio
g	acceleration due to gravity (m s^{-2})
Δh	incremental change in cake thickness (m)
n	counter
Δp	filtration pressure (Pa)
R	filter medium resistance (m^{-1})
s	mass solids concentration
t	time (s)
Δt	time interval (s)
V	cumulative volume of filtrate (m^3)
ΔV	incremental change in filtrate volume (m^3)
V_l	total volume of a layer (m^3)
V_s	volume solids concentration
V_{sc}	volume of particles joining the cake (m^3)
V_{sl}	volume of particles in a layer (m^3)
x	distance travelled by a particle (m)

Greek letters

α	specific cake resistance (m kg^{-1})
ε	porosity
μ	liquid viscosity (Pa s)
ρ_s	solid density (kg m^{-3})
ρ_l	liquid density (kg m^{-3})

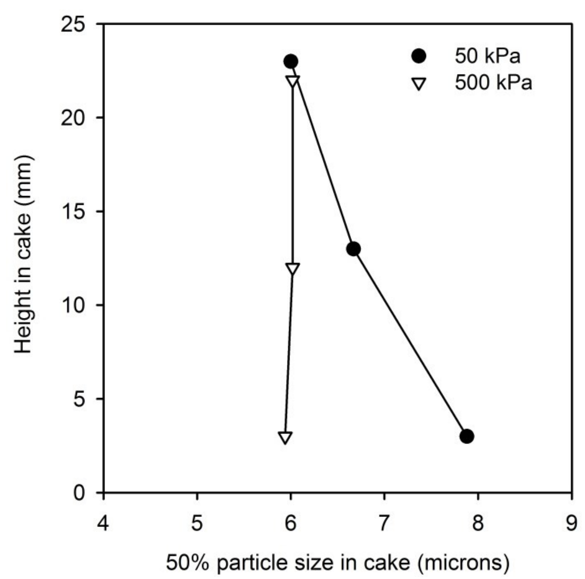

Figure 10: The effects of filtration pressure on the measured particle size in a filter cake; Feed is 'mix 2'.

Subscripts

av average value
chal challenging cake surface or filter medium
f due to filtration
max maximum value
s due to sedimentation

REFERENCES

1. Rushton A. and Rushton A., 1973. Sedimentation effects in filtration, *Filtration and Separation*, **10**, 267.
2. Clarke J.W., Kimber G.M. and Rantell T.D., 1981. The influence of particle sedimentation on filtration, *Chemical Engineering Progress*, **77**, 55.
3. Bockstal F., Fourage L., Hermia J. and Rahler G., 1985. Constant pressure cake filtration with simultaneous sedimentation, *Filtration and Separation*, **22**, 255.
4. Theliander H., 1991. On the influence of settling of particles in filtration tests – an experimental study, *Proc. FILTECH conference*, pp.339-351, Karlsruhe, The Filtration Society.
5. Tiller F.M., Hsyung N.B. and Cong D.Z., 1995. Role of porosity in filtration: XII Filtration with sedimentation, *American Institute of Chemical Engineers J.*, **41**, 1153.
6. Bothe C., Esser U. and Fechtel T., 1997. Experimental and theoretical studies on filtration with superimposed sedimentation, *Chemie Ingenieur Technik*, **69**, 903.
7. Font R. and Hernandez A., 1999. Filtration with sedimentation: Application of Kynch's theorem, *Separation Science and Technology*, **35**, 183.
8. Iritani E., Mukai Y. and Yorita H., 1999. Effect of sedimentation on properties of upward and downward cake filtration, *Kagaku Kogaku Ronbunshu*, **25**, 742.
9. Kim S.S., 1999. A theoretical and experimental study on cake filtration with sedimentation, *Korean J. Chemical Engineering*, **16**, 308.
10. Tarleton E.S. and Hancock D.L., 1997. Using mechatronics for the interpretation and modelling of the pressure filter cycle, *Trans. Institution Chemical Engineers*, **75(A)**, 298.
11. Tarleton E.S., 1999, Using mechatronics technology to assess pressure filtration, *Powder Technology*, **104**, 121.
12. Wakeman R.J., 1981. The formation and properties of apparently incompressible filter cakes under vacuum on downward facing surfaces, *Trans. Institution Chemical Engineers*, **59**(A), 260.