

The 7th World Congress on Particle Technology (WCPT7)

Characterization of bed densification in a laboratory scale thickener, by novel application of an acoustic backscatter system

Timothy N. Hunter^{a*}, Shane P. Usher^b, Simon Biggs^a, Peter J. Scales^b, Anthony D. Stickland^b, George V. Franks^b

^a*Institute of Particle Science & Engineering, School of Chemical & Process Engineering, University of Leeds, Leeds, LS2 9JT, United Kingdom.*

^b*Particulate Fluids Processing Centre, Department of Chemical and Biomolecular Engineering, The University of Melbourne, Victoria 3010, Australia.*

Abstract

The measurement of the local concentration of suspended particles within settling multiphase systems is important to many engineering applications; particularly for example in gravitational thickeners used extensively in minerals processing and water treatment. The ability to monitor concentration and stratification *in situ* may greatly aid in developing efficient separators and allow more accurate modeling of these processes. Acoustic backscatter systems (ABS) are a practical and relatively inexpensive characterization technique, with the ability to profile particle concentration as a function of depth in operational environments. Currently, such instruments are only used for sedimentology studies in dilute estuarine flows as their application in concentrated industrial suspensions is significantly more complicated and largely unstudied. A novel application is reported herein investigating the use of an ABS to characterize a model mineral separation system, utilizing a bespoke continuous flow laboratory scale thickener with inline pipe flocculator. A 1 MHz probe mounted in the near-bed region of the thickener was used to measure consolidated bed build-up and segmented density changes from the signal decay. Importantly, the influence of a scraper-rake on solids densification was observed by analyzing systems at two different scraper rotation speeds (0.1 and 1.1 rpm). An optimal rotation speed was observed that led to enhanced underflow solids fractions. Higher speeds led to an assumed fluidization of the bed from secondary flows, which reduced bed densities in the vicinity of the scraper.

© 2015 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license

(<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Selection and peer-review under responsibility of Chinese Society of Particology, Institute of Process Engineering, Chinese Academy of Sciences (CAS)

* Corresponding author. Tel.: +44-113-343-2432; fax: +44-113-343-2377.

E-mail address: t.n.hunter@leeds.ac.uk

Keywords: Acoustic backscatter system; settling characterization; concentration profiling; gravity separation

1. Introduction

Characterizing the settling and consolidation behavior of sludges and suspensions is a ubiquitous step in understanding industrial separation operations. For example, sedimentation rate and density profile information is critical to quantifying the efficiency of gravity separators in water and minerals waste processing. Much fundamental knowledge of particle settling and densification has been used to infer changes to concentration and settling velocity in such thickeners, for systems with a wide variation of particle to fluid fractions (from dilute free settling to highly hindered sedimentation and compressional consolidation). However, although some methods exist to monitor particle behavior online [1], the bulk of physical characterization studies have been on small-scale settling columns [2], and many analytical techniques are not suited to industrial scale measurement.

In fact, there is a large opportunity for the development of physical characterization techniques with the flexibility to be used *in situ* in larger separators, to both aid in process optimization and to act as real time monitors. Although a large number of papers have considered performance from a modeling and simulation perspective (e.g. [3-6]) often correlation data is derived from batch sedimentation and compressional experiments [7-10], with results being extrapolated to physical phenomena on full-scale continuous operation. This is both due to the difficulty in assessing behavior in large thickeners quantitatively, and a lack of inexpensive and robust analytical instrumentation that may be used as process monitoring equipment. However, acoustic backscatter systems (ABS) do offer a suitable technique, with the ability to gain both simultaneous interface data (similar to current echo sludge blanket monitors [11]) and concentration/density information with little intrusion. These types of devices are primarily used to study sediment transport in dilute natural environments [12], while the present authors have previously investigated their use as concentration profilers for settling and mixed industrial dispersions with particle concentrations up to ~5 v/v % [13, 14]. The potential for these devices to profile the densities of consolidated beds common in minerals thickeners is as yet unstudied, and a number of challenges exist, such as the high acoustic attenuation and signal complexity as sound is backscattered off compressed flocs in the bed.

Nevertheless, this paper details initial investigations into determining the suitability of ABS type devices to monitor densification of consolidated thickener beds over time. Experiments were conducted in a continuous flow laboratory scale thickener to enable well controlled studies using a model flocculated minerals system. Importantly, the effects of variations in the scraper-rake rotation speed were analyzed. Rakes are used in all radial flow thickeners as a means to channel underflow solids and reduce outlet blockage. However, they also improve performance by improving the density of flocculated aggregates, increasing final bed density. While quantitative characterization of the role of rakes in controlling bed densities in full scale systems is sparse, previous work on a pilot scale thickener has shown a strong correlation between rake speed and underflow solids fraction [15].

2. Experimental

A bespoke continuous laboratory-scale thickener at the University of Melbourne was utilized, as has been described in detail elsewhere by the authors [16, 17]. Briefly, it incorporates a Perspex column ~1.2 m high and 0.3 m in diameter with an addition of a fitted metal cone that allows for underflow discharge. To reduce blockages near the underflow it also incorporates two small scraper-rakes (1 cm high by 1 cm wide) that rotate around the base of the cone from a centrally mounted mixing rod. The column is fed by a 100 L feed tank connected to a peristaltic pump capable of high solids suspensions. Feed suspensions are diluted by use of a secondary monopump connected to a tap water stream. The underflow is pumped to a similar 100 L waste tank using an identical peristaltic pump to the feed. The clarified overflow is gravity fed to a drain. By appropriate operation of feed and underflow pumps, pseudo-continuous performance of the column can be achieved for periods of time until exhaustion of the feed tank (in this study ~5 hours).

To operate the column, 30 kg of fine calcite (approx. 2 micron average size, Omycarb 2 from Omya Industries) was first mixed with 30 kg water in the feed tank. The feed pump was then set at a rate of 10 L/hr and the feed was

diluted from a large flow of the fresh-tap inlet, giving an overall flow rate of 110 L/hr. Anionic polymer (AN 934SH) from SNF Chemicals was injected into the diluted feedline to flocculate the calcite. The polymer has previously been used as a strong flocculation agent for calcite [10] and here a stock solution of 1000 ppm concentration was injected at such a rate to dilute it to 40 ppm on solids in the feed line. The calcite-polymer mix was then pumped 6 meters (through 10 mm ID tubing) to the column inlet, which created optimized shear conditions to flocculate [18, 19]. Due to the high efficiency of the polymer and low bulk flux rate through the column, the aggregates appeared to settle in a low concentration unhindered free-settling zone. The underflow was initially set at a low rate (at around 1/3 the feed rate) and a consolidated sediment bed allowed to build up in the column to ~15 cm, before the underflow rate was set to match the concentrated feed, and bed height equilibrium was established. Samples of the feed, column underflow and overflow were taken at regular time periods. Importantly, two separate runs were undertaken with the column scraper speed set at 0.1 and 1.1 rpm respectively, to observe how variation in rake speed influences bed densities. A third run was also completed with the scraper turned off completely.

To analyze the density of the consolidated beds, an Aquascat1000 acoustic backscatter system (ABS) was employed (Aquatec Group Inc). Here, a 1 MHz transducer head was mounted at about 20 cm above the base of the column, at a height slightly above the consolidated sediment bed interface. Acoustic penetration and attenuation was measured from the ABS (at 64 Hz pulse frequency) and averaged into 15 minutes time-steps. The ABS was set to analyze the bed throughout the five hours of thickener operation.

3. Results & Discussion

3.1. Interface, penetration and bulk density

The ABS data was first analysed to aid understanding of the suitability of the instrument for observing bed densification *in situ*. Fig. 1 gives an example of the raw data from the instrument, and shows the echo backscatter strength versus distance from the probe for 15 minute averages representing the final consolidated beds (at t +225 min) for runs at the two different scraper speeds.

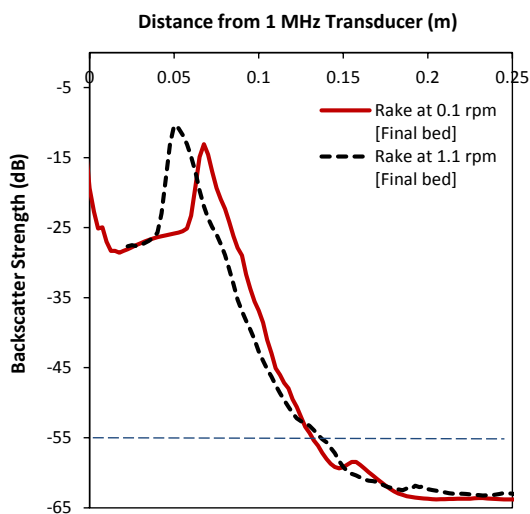


Fig. 1. Backscatter decay for the 1 MHz probe as a function of vertical distance through the final consolidated beds at both scraper-rake speeds. Dashed horizontal line represents instrument noise threshold.

It is clear from Fig. 1 that the backscatter reaches a peak representing the interface of the consolidated settled

bed with the free-settling suspension above it, whereupon the signal then decays as it attenuates through the bed. By analysing the change in the vertical position of the peak, the evolution of the height of the bed interface can be easily monitored with time. Fig. 2 shows the averaged position of this peak distance plotted in terms of distance from the base of the column for both runs. The data suggests that a similar equilibrium height was established at around $t + 150$ min for both runs (the initial negative distances represent the bed building through the cone at the base of the column). It is noted that for the run with the scraper at 0.1 rpm, the underflow was initially set at a very low rate (of ~ 1.7 L/hr) but due to some issues with clogging in the underflow pipe this was doubled at ~ 50 minutes to 3.3 L/hr. For the run at 1.1 rpm, the underflow rate was only set at 3 L/hr until the bed height was equilibrated.

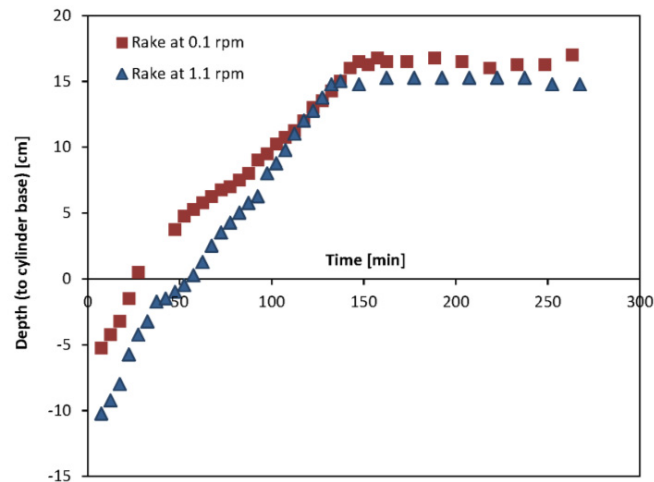


Fig. 2. Change in consolidated bed height with time, as measured with the ABS for the two runs at different scraper speeds.

A second important aspect of the ABS analysis was to understand how the instrument may be used to measure density profile through the sediment bed and how this changes with time (bed densification). Initially, the penetration of the acoustic pulse was analysed by measuring the distance between the bed interface and the bed depth to attenuate the echo signal to a -55 dB level (shown by the dashed horizontal line in Fig. 1) as a route to qualitatively observe differences to the bulk density. This level was chosen as effectively the noise threshold of the instrument. Although signals weaker than -55 dB are measured by the device, they deviate in linearity due to the material resistance affecting the conversion from the acoustic echo to generated voltage [20]. Effectively then, this gives a simple way of estimating the average density of the bed, as greater penetration distance should correlate to a higher overall voidage fraction or lower solids concentration in the bed. Fig. 3 displays how the average penetration depth for the two runs changed with time.

First, the results of the rake at 0.1 rpm are discussed briefly. It is observed that the penetration depth increased after 150 minutes (when the bed reached an equilibrium height) and indicates that initially the bed density reduces when the underflow is increased, which is to be expected. At longer time periods there is a slight reduction in the average penetration depth indicating some bed consolidation. Unfortunately, the run with the rake set to 1.1 rpm gave some operational problems. Air bubbles got caught on the probe around the time the underflow was increased, which led to a large reduction in the backscatter strength (as trapped air highly attenuates acoustic signals) and data at intermediate time periods could not be analysed. However, at further time periods the probes were degassed by shaking successfully, and a clear increase in penetration is observed in relation to the rake at 0.1 rpm. Hence, it appears that the faster rake speed actually leads to a lower bed density. This was opposite to what was initially expected, as it was assumed that a faster scraper speed would increase the mechanical floc densification force, thus leading to smaller, denser flocs and lower voidage.

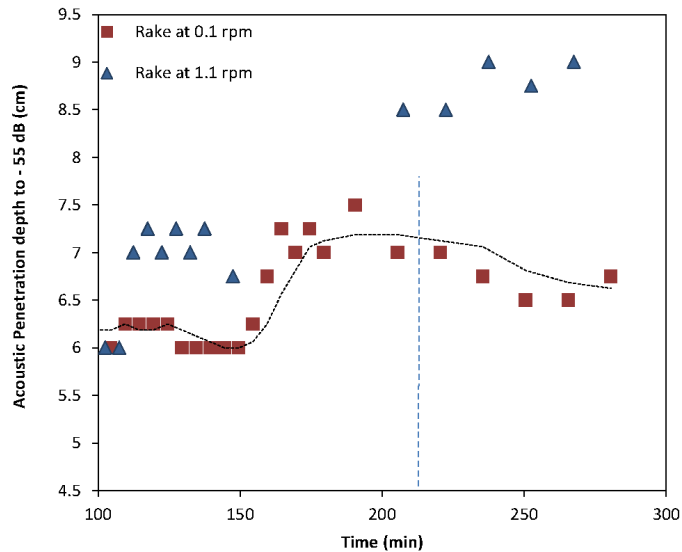


Fig. 3. Analysis of changes to the acoustic penetration depth over time, for the two scraper speeds. Dotted trendline represents smoothed average for run at scraper set to 0.1 rpm, while dashed vertical line represents approximate time where equilibrium height is reached for both runs.

There is a caveat to understanding results from this averaging technique however, as the 1 MHz probe could only penetrate through ~50% of the bed depth (with penetration distances for the 0.1 rpm scraper speed at only 7 cm for example). This restriction meant it was not possible to measure changes closer to the rake's position. Due to these limitations, and to help compare results from the ABS, samples of the underflow were also taken in parallel for each run (from an outlet below the thickener). The concentration of solids was determined by weight loss upon drying the samples. Fig. 4 shows the measured sampled solids concentrations as a function of time for the same runs as the ABS analysis (with scraper speeds set to 0.1 and 1.1 rpm). Also given are concentrations relating to a run with the scraper turned off completely for comparison (no ABS data was taken with this run).

It is noted from Fig. 4 that the underflow concentration data for the scraper set at 0.1 and 1.1 rpm correlate well with the ABS data. Again, solids density is consistently higher with the scraper at 0.1 rpm, and also, both systems show a distinct decrease in density values when the underflow pumping rate is increased at $t + 150$ min, when the equilibrium height is set (also consistent with the ABS data). Interestingly however, the density values for the system without a moving scraper are significantly lower. Therefore, it appears there is a peak scraper speed in this system, where the mechanical force is densifying floc structures, but not creating flocculated aggregate breakup or secondary flow disruptions, which may reduce the efficiency of the raking process.

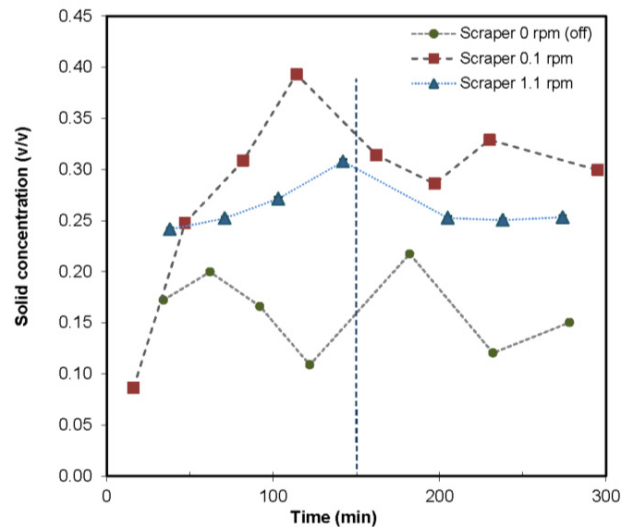


Fig. 4. Underflow sampled concentration as a function of time for thickener runs with scraper set to 0, 0.1 and 1.1 rpm. Dashed vertical line represents approximate time where equilibrium height is reached.

3.2. Segmental attenuation measurements

Although it was clear the ABS correlated to underflow sampling measurements, it was important to determine whether more quantitative analysis could be extrapolated, to enhance analysis of the complex interactions of the scraper in controlling bed densification. Specifically, information about the density profile as a function of depth would aid in understanding the role of raking in sediment consolidation. Hence, the ABS profiles were analyzed to look for segmental changes in bed density, which may elucidate information about where within the bed the scraper may be influencing underflow voidage. To do this, the acoustic attenuation was measured in 22 mm segment intervals (approximated from the linear dB decay at each depth) between the signal peak at the bed interface to the total penetration depth (at -55 dB) for both runs.

It is noted that, as can be observed in Fig. 1, attenuation through the bed (signal loss with distance) follows an approximately logarithmic relationship. For higher frequency probes, these consolidated particle beds (where attenuation dominates) would be expected to show linear decay trends (on the given dB scale) or in other words, show a depth independent signal relationship [13, 14]. The relatively low 1 MHz frequency used however shows a depth dependent relationship, due to the influence of both scattering and attenuation on the signal. This means that quantification of the signal loss due to a specific particle concentration is difficult, as the attenuation will naturally reduce with distance from the probe even for beds with constant voidage. However, it is possible to compare signal loss variation at particular depths for different systems. Also, as attenuation in the low concentration region above the bed is negligible for these small distances, we can directly compare runs for the scraper set to 0.1 and 1.1 rpm, by analysing similar distance segments in relation to the bed interface.

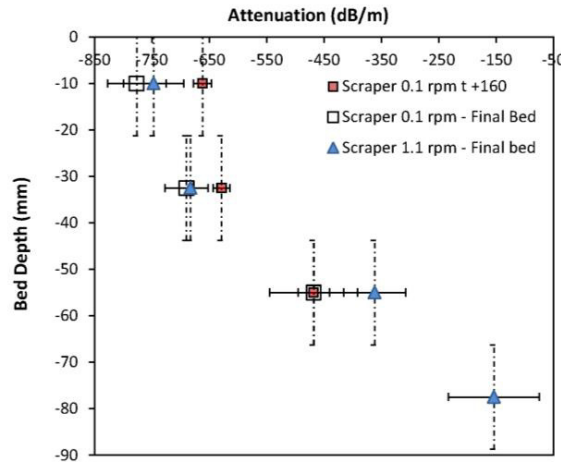


Fig. 5. Comparison of segmental attenuation through the final consolidated beds as measured with the ABS, for thickener runs set with both scraper speeds, as well as an intermediate time period with the scraper set at 0.1 rpm. Higher magnitude attenuation corresponds to higher density at any given depth.

Fig. 5 gives a comparison of the segmental attenuation for the final consolidated beds for both runs, along with the attenuation for the consolidated bed at $t + 160$ minutes for the 0.1 rpm scraper run. The points shown represent averages of two 15 minute time-steps (i.e. $t + 160$ min represents t 145-160 and t 161-185) and horizontal error bars represent the standard deviation between the two time averages. The vertical error bars simply indicate the total depth segment that attenuation was calculated over.

For all trends shown in Fig. 5, it is clear that attenuation does decrease in magnitude in an approximately logarithmic fashion with depth (from the top bed interface at 0 mm). This does not, of course, mean that concentration decreases (as the bed density will increase with depth) only that for a given concentration, the measured attenuation is depth dependent. However, even though the actual attenuation values are dependent on both concentration and depth, it has been shown previously [13] that for a given depth, changes in attenuation can still be linearly correlated to concentration. Hence, comparatively between the runs shown, an increase in attenuation can be directly attributed to an increase in relative concentration and vice versa.

For the run with scraper speed of 0.1 rpm, the slight increase in attenuation within the upper segments of the bed from $t + 160$ to t final suggests some consolidation over time (consistent with the average penetration and sample results) although again it is emphasised that overall penetration depth is low (~ 70 mm) and changes nearer the scraper cannot be analysed. More importantly, the apparent reduction in concentration when the scraper was set at 1.1 rpm can be more clearly seen segmentally. It appears that while higher up in the bed the attenuation for both runs is similar, there is a considerable reduction in attenuation lower down, suggesting a relatively lower particle concentration. In respect to the upper segments of the bed, results indicate a less significant increase in density with depth for the scraper set at 1.1 rpm than for 0.1 rpm within the lower bed regions (though without further correlation tests this cannot be verified). Hence, the scraper appears to be affecting the bed density more within its local vicinity, although again, we cannot visualise the area directly above it.

From these results, it appears that the faster scraper is fluidising the bed around it, causing secondary flow interactions that increase the voidage. It must be stated that for this dual-scraper, a rotational speed of 1.1 rpm is relatively fast, so perhaps it would not be surprising that flow disruption is occurring. However, it would also naturally be expected that the scraper movement would cause densification of the packed bed, although floc breakup may also be expected at higher rotation rates. The latter has been shown to be detrimental to dewatering performance [21]. Previous work looking at thickening using vertical rakes (with forked poles that penetrated through the entire consolidated bed) showed a clear increase in bed density with rotation speed [15], albeit only up to a raking rate that had been deemed to cause minimal floc breakage. This highlights the importance of both rake design and operation on optimising thickener performance. What has been shown in the current study however is the

potential for ABS type devices to measure these performance factors non-intrusively, and thus aid in design analysis and monitoring.

4. Conclusions

This report has detailed the novel application of an acoustic backscatter system (ABS) to analyze density as a function of depth and time within a consolidated laboratory scale thickener bed, as scraper-rake rotation speed was varied (at 0.1 and 1.1 rpm). Both average penetration depths, as determined from the ABS, and underflow sampling measurements correlated well, and suggested that the optimum scraper speed was 0.1 rpm to enhance bed densification by densifying floc structures and without causing secondary flows. The ABS was further able to analyze the voidage segmentally through attenuation measurements, and indicated that relative changes to bed density were more significant deeper within the vicinity of the scraper. However, a large caveat in the current ABS configuration was that the probe could only penetrate to approximately half the total bed depth (due to the strong signal decay) and information from the area directly above the scraper was unable to be determined. A future program of work will look to overcome these limitations by placing a number of probes horizontally up the side of the thickener column. This configuration will enable much greater resolution at multiple bed heights and also allow more quantitative comparison of different scraper-rake designs.

Acknowledgements

Acknowledgements are given to the EPSRC *Bridging the Gap* program for partial funding of this project, as well as the University of Melbourne and Sellafield Ltd for further direct financial support. Thanks are also given to Aurelien Zmely and the University of Melbourne engineering technical support for their assistance in the conduction of the experiments.

References

- [1] Vanrolleghem, P.A., J. De Clercq, B. De Clercq, M. Devisscher, D.J. Kinnear, and I. Nopens, New measurement techniques for secondary settlers: A review, *Water Science & Technology* 53 (2006) 419-429.
- [2] Garrido, P., R. Bürger, and F. Concha, Settling velocities of particulate systems: 11. Comparison of the phenomenological sedimentation-consolidation model with published experimental results, *International Journal of Mineral Processing* 60 (2000) 213-227.
- [3] Ebrahimzadeh Gheshlaghi, M., A. Soltani Goharizi, A. Aghajani Shahriyar, and H. Abdollahi, Modeling industrial thickener using computational fluid dynamics (CFD), a case study: Tailing thickener in the Sarcheshmeh copper mine, *International Journal of Mining Science and Technology* 23 (2013) 885-892.
- [4] Rudman, M., D.A. Paterson, and K. Simic, Efficiency of raking in gravity thickeners, *International Journal of Mineral Processing* 95 (2010) 30-39.
- [5] Verrelli, D.I., D.R. Dixon, and P.J. Scales, Assessing dewatering performance of drinking water treatment sludges, *Water Research* 44 (2010) 1542-1552.
- [6] Zhang, Y., A. Martin, and P. Grassia, Prediction of thickener performance with aggregate densification, *Chemical Engineering Science* 101 (2013) 346-358.
- [7] D. Stickland, A., C. Burgess, D.R. Dixon, P.J. Harbour, P.J. Scales, L.J. Studer, and S.P. Usher, Fundamental dewatering properties of wastewater treatment sludges from filtration and sedimentation testing, *Chemical Engineering Science* 63 (2008) 5283-5290.
- [8] O'Shea, J.-P., G.G. Qiao, and G.V. Franks, Temperature responsive flocculation and solid-liquid separations with charged random copolymers of poly(N-isopropyl acrylamide), *Journal of Colloid and Interface Science* 360 (2011) 61-70.
- [9] Usher, S.P., L.J. Studer, R.C. Wall, and P.J. Scales, Characterisation of dewaterability from equilibrium and transient centrifugation test data, *Chemical Engineering Science* 93 (2013) 277-291.
- [10] van Deventer, B.B.G., S.P. Usher, A. Kumar, M. Rudman, and P.J. Scales, Aggregate densification and batch settling, *Chemical Engineering Journal* 171 (2011) 141-151.
- [11] *AWWA, Instrumentation and Control - Manual of Water Supply Practices, M2* (3rd Edition), American Water Works Association (AWWA), 2001.

- [12] Thorne, P.D. and D. Hurther, An overview on the use of backscattered sound for measuring suspended particle size and concentration profiles in non-cohesive inorganic sediment transport studies, *Continental Shelf Research* 73 (2014) 97-118.
- [13] Hunter, T.N., L. Darlison, J. Peakall, and S. Biggs, Using a multi-frequency acoustic backscatter system as an in situ high concentration dispersion monitor, *Chemical Engineering Science* 80 (2012) 409-418.
- [14] Hunter, T.N., J. Peakall, and S. Biggs, An acoustic backscatter system for *in situ* concentration profiling of settling flocculated dispersions, *Minerals Engineering* 27-28 (2012) 20-27.
- [15] Gladman, B.R., M. Rudman, and P.J. Scales, The effect of shear on gravity thickening: Pilot scale modelling, *Chemical Engineering Science* 65 (2010) 4293-4301.
- [16] Forbes, E., J.-P. O'Shea, M. Vetterli, and G.V. Franks. Design of a pilot-scale thickener column for evaluating temperature controlled flocculation/dispersion. in *Chemeca*. 2011.
- [17] Franks, G.V., J.-P. O'Shea, and E. Forbes, Controlling thickener underflow rheology using a temperature responsive flocculant, *AIChE Journal* 60 (2014) 2940-2948.
- [18] Heath, A.R., P.A. Bahri, P.D. Fawell, and J.B. Farrow, Polymer flocculation of calcite: Population balance model, *AIChE Journal* 52 (2006) 1641-1653.
- [19] Owen, A.T., P.D. Fawell, J.D. Swift, D.M. Labbett, F.A. Benn, and J.B. Farrow, Using turbulent pipe flow to study the factors affecting polymer-bridging flocculation of mineral systems, *International Journal of Mineral Processing* 87 (2008) 90-99.
- [20] Smerdon, A.M. and S.M. Simmons. Testing the limits of a multi-frequency acoustic sediment profiling instrument. in *Underwater Acoustic Measurements - 3rd International Conference & Exhibition Series*. 2009. Nafplion, Greece.
- [21] Gladman, B., R.G. de Kretser, M. Rudman, and P.J. Scales, Effect of Shear on Particulate Suspension Dewatering, *Chemical Engineering Research and Design* 83 (2005) 933-936.