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Recent developments in techniques and methodologies for improving thickener performance

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Abstract

Research projects directed towards 'Improving Thickener Technology' have been conducted by the AJ Parker Cooperative Research Centre for Hydrometallurgy since 1988 through the Australian Mineral Industries Research Association with support from 25 Australian and international mineral processing companies. These projects have resulted in the development of a range of research tools and techniques to address flocculation and thickening issues. Laboratory and plant studies have focused on how key factors, such as mixing intensity, mixing duration and solids concentration, affect flocculation efficiency and, hence, thickener performance. A comprehensive computational fluid dynamics (CFD) model has been developed to predict likely full-scale performance under various process conditions, based upon a knowledge of thickener design, plant flows and laboratory assessment of the flocculation behaviour of the feed slurry. Application of this CFD model to problems within specific mineral processing operations has resulted in significant benefits, in one case leading to doubling of a thickener's throughput. This paper presents an overview of the work conducted during these projects, focusing on the research tools, the nature of the information that has been gained and the implications for thickener performance. Brief details will be presented on research issues currently being investigated.

Keywords: Flocculation; Thickener technology; Computational fluid dynamics

1. Introduction

Gravity thickening is a key step in many hydrometallurgical processing operations. The principle is simple, involving addition of flocculant to aggregate fine particles, thereby enhancing their settling under gravity to produce a clear liquor and a concentrated underflow suspension. However, the approach to optimising the performance of thickeners has usually been ad hoc, involving 'fiddling' with flocculant sparge points or making 'try it and see' feedwell modifications.

Research aimed at improving the understanding of the fundamental processes occurring within full-scale gravity thickeners was initiated by the Parker Centre in 1988 through the Australian Mineral Industries Research Association (AMIRA) coordinated 'Improving Thickener Technology' P266 project.

The early stages of the research focused on developing techniques to measure the properties of aggregates formed in full-scale thickeners under different operating conditions, and on viable methods to alter aggregate structures to optimise performance. A principal outcome was the identification of the dominant influence that agitation conditions, used to mix the flocculant with the feed, have on the properties of the flocculated suspension and, hence, thickener performance. The prototype 'shear vessel' developed in the course of this work [1] has become an important laboratory tool for flocculation research.

Subsequent stages of the research investigated how specific thickener performance issues, such as throughput, underflow density and flocculant consumption, were related to the mixing conditions used to flocculate the feed. Laboratory studies coupled with site work were used to determine the significance of mixing intensity, residence time and other factors on the flocculation states achieved with selected mineral suspensions. At the same time, the hydrodynamic conditions prevailing within full-scale feedwells were characterised by computational fluid dynamics (CFD) models that were validated using tracer studies and feedwell sampling. Comparisons between plant and laboratory flocculation performance indicated that there was considerable scope to improve full-scale operation through optimisation of feedwell flocculation conditions. One very tangible outcome was the use of this improved understanding to modify a sponsor's thickener, resulting in a doubling

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of the throughput and avoiding the need to install new thickeners during a plant expansion [2].

Quantification of the effect that feedwell flocculation conditions have on thickener performance was obtained in work conducted at a mineral sands site (Westralian Sands, Capel, Western Australia) using twin tailings thickeners. In this work, one thickener was used as a control, and its performance was compared with the performance obtained in the other thickener when the feed was flocculated under different hydrodynamic conditions. The results confirmed that full-scale performance is very sensitive to the nature of the hydrodynamic conditions during flocculation, but also highlighted the complex influence that the feed solids concentration, liquor recycling, the agitation intensity profile and agitation duration have upon the resulting aggregation state.

A number of key research issues are being explored in a new 3-year AMIRA project involving a team of chemists, process engineers and fluid dynamists. This work is supported by 18 companies, covering a range of mineral processing operations (alumina, base metals, uranium, mineral sands, etc.) plus thickener manufacturers and a flocculant supplier. One new research direction aims to improve the CFD model's ability to predict full-scale performance by including the capability to model the formation and rupture of aggregates under different hydrodynamic conditions. Flocculation kinetics data under a range of conditions is being obtained for the model from measurements made under turbulent pipe flow conditions using well-characterised substrates. Another new direction concerns rake operation, aiming to gain an understanding of the optimum blade configuration and rake structure for promoting densification, while at the same time maximising solids discharge and minimising rake torque. Coupled to this laboratory work are site-based activities, involving the evaluation of new thickener designs, sediment consolidation studies and the measurement of the flocculation kinetics of plant materials.

In the remainder of this paper, an outline is given of some of the tools and techniques that have been applied to the study of flocculation processes and their use to optimise the performance of full-scale thickeners within the AMIRA 'Improving Thickener Technology' projects. An insight will be given into the nature of these tools, the information that has been gained and the implications for the performance of full-scale thickeners.

2. Flocculant characterisation

Despite the extensive use of ultra-high molecular weight flocculants in mineral processing, their physical properties remain poorly understood. In particular, little is known about their molecular weight distributions, due to the difficulties involved in characterising large, shear sensitive polymers. Such information is essential to understand and predict flocculant performance.

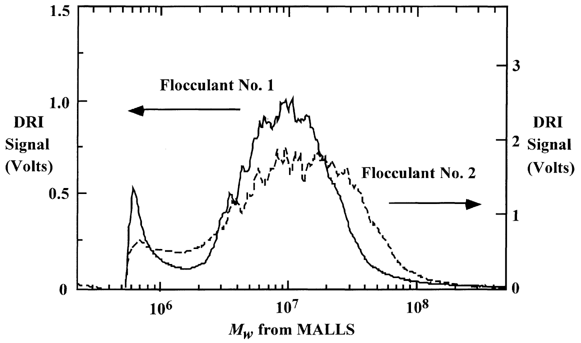

Fig. 1. Molecular weight distributions of two commercial non-ionic flocculants measured by FlowFFF combined with MALLS, showing the response from the concentration-sensitive differential refractometer detector.

The technique of flow field-flow fractionation (FlowFFF) has been successfully applied to the determination of flocculant molecular weight distributions [3,4]. In contrast to conventional packed column chromatography, FlowFFF makes use of an open channel and low exposed surface (<0.01 m^2), limiting shear and reducing losses from adsorption. Separation results from the application of a perpendicular cross-flow, with smaller species able to diffuse against the cross-flow and therefore occupy faster moving laminae of the carrier flow. This enables efficient separation over a very wide range of molecular weights.

The use of multi-angle laser light scattering (MALLS) as a detector allows the direct determination of the molecular weight from each eluted volume slice. A clear relationship between molecular weight and elution time has been observed, and was generally independent of the polymer source. The measured molecular weight distributions for two commercial non-ionic flocculants are presented in Fig. 1, which shows the breadth of molecular weights found in each product. Elution can be complicated by the presence of agglomerated polymer, a feature observed in a number of polyacrylamide solutions. Such agglomerates may be eliminated by careful control of the solution composition [4].

A number of flocculants have been examined by FlowFFF, each giving distinct elution profiles. This information has been used to explain why flocculants of similar average molecular weight behave quite differently. The flocculant molecular weight distributions from FlowFFF, linked to the aggregate characterisation techniques described later, are providing the basis for predicting flocculant performance from the inherent physical properties of flocculants.

3. Characterising flocculated suspensions

The effectiveness of most gravity thickeners in the mineral processing industry relies upon the ability of a flocculant to aggregate the fine particles within the feed suspension into clusters, commonly called 'flocs'. Flocculation of a suspension produces a broad range of aggregate

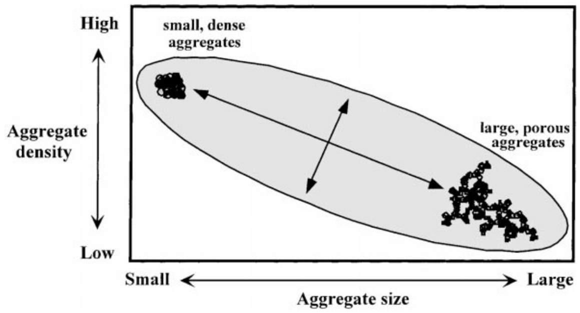

Fig. 2. Schematic of the range in the size and density of aggregates produced by flocculation of a mineral suspension prior to gravity thickening.

structures that vary in size and density (see Fig. 2), and exhibit extreme shape irregularity. These properties have a profound effect upon suspension dewatering properties, controlling the settling rate, consolidation and rheology. Effective measurement of aggregate properties in flocculated suspensions is complicated by their fragile nature, and utmost care needs to be taken that the measurement technique itself does not change their size or structure.

3.1. Measuring aggregate size distributions

A number of techniques have been tried for measuring aggregate size distributions [5], including standard particle sizing methods based on laser light scattering (e.g. Malvern Mastersizer) and sedimentation (e.g. Sedigraph). None have proved successful due to break-up of the aggregates within the measurement system. Application of a relatively new technique, Focused beam reflectance measurement (FBRM), has been more successful, allowing in-situ characterisation of aggregate 'sizes' (1–1000 μm) at a wide range of solids concentrations (2–70 wt.%). The principle of operation of this technique is shown schematically in Fig. 3.

A highly focused laser beam is projected through a sapphire window and rapidly scans at a fixed velocity across any particle or aggregate flowing past the probe window. The duration of the reflected light can be related to an aggregate's chord length. Scanning several thousands of aggregates per second allows the rapid determination of the aggregate chord length distribution.

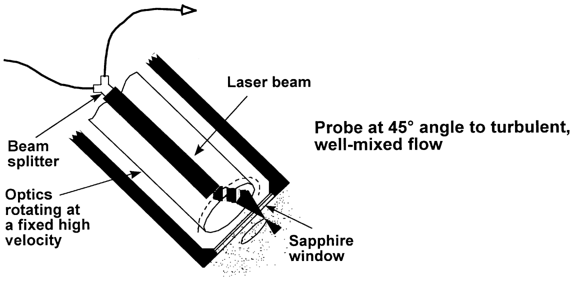

Fig. 3. Operating principle of the FBRM probe for determining aggregate size distributions.

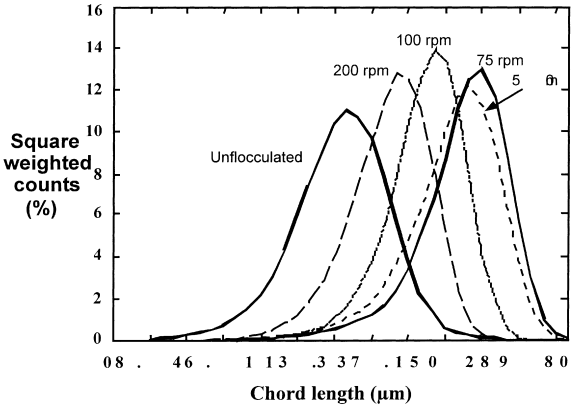

Fig. 4. Effect of flocculation conditions on square-weighted aggregate size distributions measured in situ by FBRM. Flocculation achieved in the shear vessel at constant flocculant dosage but using different agitation intensities during contact of the flocculant and feed.

The FBRM technique can indicate the extent of flocculation under different conditions (e.g. different flocculant dosages, mixing conditions, etc.). Fig. 4 shows an example of this, where the FBRM aggregate size distributions achieved using the same flocculant dosage, but different mixing conditions during contact of the flocculant with the feed, are compared with those of the primary (non-flocculated) particles. This technique was also used successfully within full-scale thickeners to determine the extent of flocculation in different parts of the feedwell. Importantly, a direct correlation was established between the average chord length and the settling rate [6]. Thus, the on-site use of the FBRM technique to identify the conditions that result in the largest chord length distribution offers a new approach to optimising thickener performance for a given flocculant-feed system.

3.2. Measuring aggregate settling rates

Overflow clarity is a key operating criterion in many mineral processing operations, especially where solid–liquid separation by gravity thickening precedes precipitation (e.g. Bayer refineries), electrowinning (zinc refineries) or solvent extraction (e.g. nickel laterite operations).

The cause of unusually high thickener overflow solids can be easily resolved using a video/magnification system to measure the size and settling of the solids in the overflow liquor under static hydrodynamic conditions [5]. This simple but powerful diagnostic approach can identify whether the high overflow solids are due to:

- poor flocculation (as indicated by the presence of unflocculated particles);
- flotation (air bubbles are seen entrained within aggregates);
- undispersed flocculant 'fish-eyes' (particles are seen attached to globules of gel);
- aggregate rupture (evident from the presence of small, slow settling aggregates); or

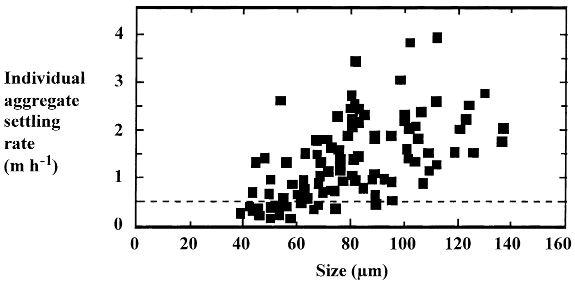

Fig. 5. Measured settling rate of aggregates present in a clarifier's overflow at a zinc refinery during 'normal' operation. The horizontal broken line represents the average rise velocity in the clarifier under the prevailing operating conditions.

- fluid short circuiting to the overflow (indicated by the presence of aggregates that settle faster than the nominal average rise velocity of the thickener).

Measurements demonstrating the latter cause were made on a clarifier at a zinc refinery during 'normal' operation (Fig. 5). The horizontal broken line represents the average rise velocity in this clarifier for the prevailing operating conditions (i.e. feed flow rate and underflow rate). It is clear that there is a high proportion of aggregates with settling rates much faster than the clarifier's average rise velocity. The presence of these aggregates in the overflow indicates there are streams of liquor moving to the overflow at up to eight times the average liquor velocity, i.e. flow short circuiting. Subsequent CFD modelling (discussed later) of the clarifier's feedwell identified that the cause of the flow short circuiting was the significant asymmetry of the discharge from the (open) feedwell due to the angle of entry of the feed-pipe [7], as shown in Fig. 6.

4. Role of hydrodynamics in flocculation

The mixing conditions used to contact the flocculant with particles to induce aggregation are critical to the efficiency of flocculation and, hence, thickener performance. A versatile laboratory instrument, the 'shear vessel' (see Fig. 7), has been developed to provide an insight as to how mixing conditions (intensity and duration) affect flocculation performance [1]. The instrument, based upon Couette geometry, involves contacting the flocculant and the feed suspension within the gap of concentric cylinders. The mixing intensity is selected by changing the speed at which the inner cylinder is rotated; the mixing duration is altered by changing the flow rate or by changing the point at which the flocculant is added (ports 1–4, Fig. 7).

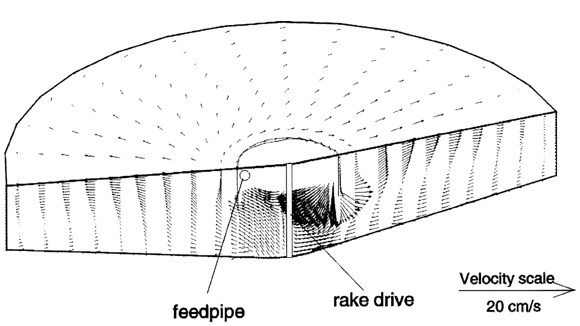

Fig. 6. Steady-state flow field obtained from computational fluid dynamics showing a strong radial flow from feedwell opposite the feed pipe. Toroidal vortex pattern clearly evident in the settling zone.

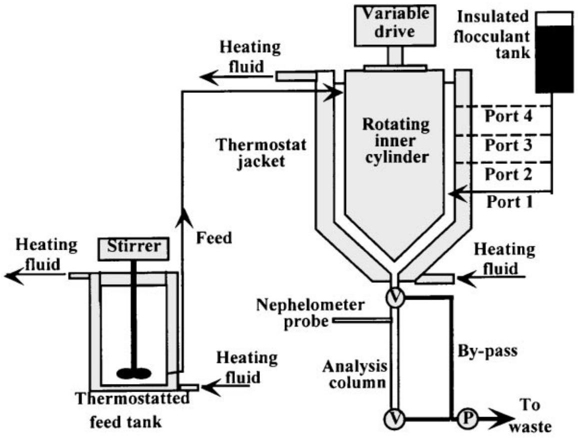

Fig. 7. Schematic of the shear vessel system for determining the effect of agitation conditions on flocculation performance.

An example of the information that can be obtained with the shear vessel is given in Fig. 8. The data shows that the flocculation efficiency (settling rate and residual turbidity) depends strongly on the mixing intensity (rotation speed) during contact of the flocculant and the feed. The different flocculants have distinct mixing requirements for optimal performance, undoubtedly due to differences in their adsorption characteristics on the mineral surfaces. Mixing intensity during flocculation is therefore an important parameter to consider with respect to full-scale performance [8].

A linear pipe reactor system has also been developed to investigate the kinetics of flocculation, enabling the optimum time for mixing the flocculant and the feed to be identified. With this technique, flocculant is introduced into a pipe through which the feed suspension flows at a set rate, and aggregate 'size' measurements are made downstream using the FBRM probe in order to determine the rate at which the aggregates grow and rupture under given process conditions. An example of the type of information obtained from the linear pipe reactor system is given in Fig. 9, showing the change in aggregate average chord length as a function of reaction time under two flocculation conditions. Under high shear conditions (curve a), the average aggregate 'size' grows rapidly from 30 to about 130 μm in 15 s, before aggregate rupture dominates leading to a steady decline in the 'size'. With low shear conditions (curve b), the aggregate growth rate is much slower, with the average 'size' increasing steadily to 100 μm over 50 s with no evidence of aggregate rupture becoming dominant.

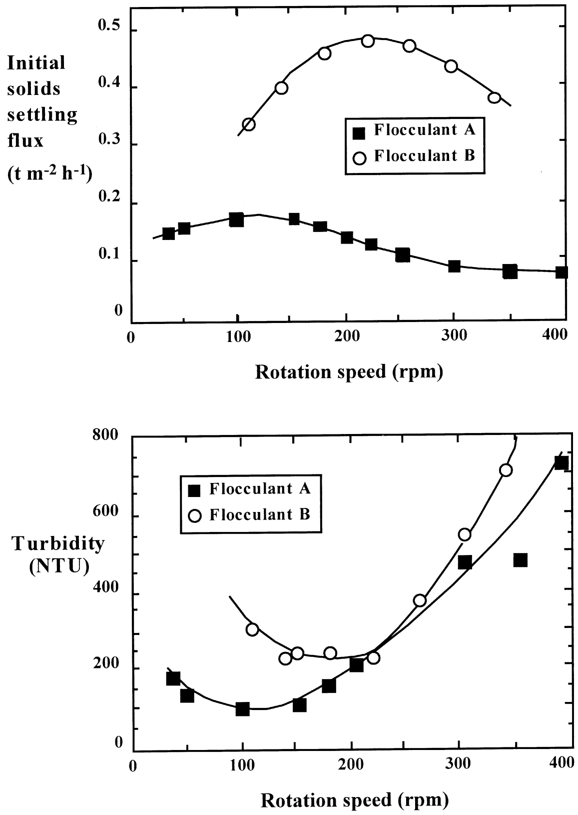

Fig. 8. Flocculation performance as a function of agitation intensity using two chemically different flocculants and a tailings suspension from a diamond operation.

These differences observed in the aggregate growth rate have significant implications for the performance of full-scale thickeners. Optimum performance will only be obtained if the flocculation reaction within the feedwell reaches completion (i.e. the maximum aggregate size is obtained) as the suspension discharges into the quiescent settling zone of the thickener. For flocculation under high shear conditions (Fig. 9a), the suspension would need 15 s for maximum aggregation before discharging into the quiescent settling zone. For flocculation under low shear conditions (Fig. 9b), the required time is at least 50 s (for this solids concentration, flocculant type and dosage, etc.).

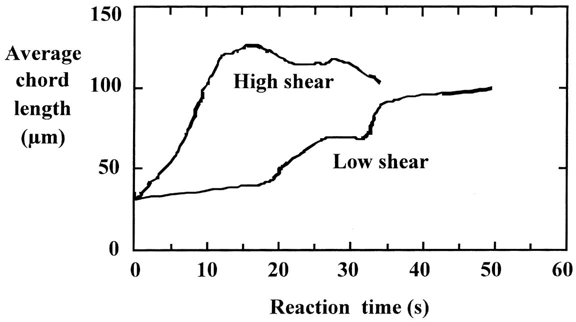

Fig. 9. Flocculation kinetics data for the growth and rupture of aggregates under (a) high and (b) low shear conditions.

A key consideration in feedwell design is therefore the available ‘reaction’ time between flocculant addition and discharge into the settling zone of a thickener, and must accommodate the specific flocculation kinetics of a given slurry/flocculant combination under a range of hydrodynamic conditions.

5. Understanding full-scale performance

Three-dimensional, two-phase CFD models have been developed in the AMIRA ‘Improving Thickener Technology’ projects to map fluid flow patterns in thickener feedwells [2,9]. The models require input of the geometric dimensions of the feedwell plus process conditions such as flow rates, feed solids concentration, liquor density and viscosity. At this stage of development, a number of simplifications are made, such as assuming a single particle size and particle density. A flocculant adsorption equation has been recently incorporated into the CFD model to describe the flocculant-particle interaction.

Once the flow field has been computed, the CFD model can be used to predict the shear rate distribution, solids distribution, flocculant adsorption profile, etc. within the feedwell and the surrounding regions of the thickener. Examples for particular full-scale feedwells are shown in Fig. 10 (shear rate distribution), Fig. 11 (solids concentration distribution) and Fig. 12 (free flocculant profile). With this information, the impact of engineering modifications, such as a change in the diameter of the feedwell or a change to the entry angle of the feedpipe, can be readily assessed.

The model is also a powerful tool for predicting the best location to place the flocculant sparge outlet within the feedwell, but this requires an understanding of the flocculation behaviour (e.g. Fig. 8) and kinetics (e.g. Fig. 9) for a particular feed slurry/flocculant combination.

An important aspect of the CFD modelling work is full-scale validation. This involves releasing tracers (preferably both liquid and solids) into the feed stream entering the feedwell and sampling the flows exiting the feedwell at a different position. The time trend of the tracer signal has been found to be in good agreement with that predicted by the CFD model [2]. If this was not the case, then the model would be failing to account for all factors affecting full-scale performance.

Application of these CFD modelling techniques has resulted in significant improvements in the performance of full-scale thickeners. However, the model is still at an early stage of development and one aim of the latest AMIRA ‘Improving Thickener Technology’ project is to improve the CFD model’s predictive capabilities, especially through incorporation of better flocculation kinetics data.

One example of how the model was used to improve full-scale performance at Worsley Alumina Limited (Collie, WA, Australia) has been described in detail by Kahane et al. [2]. In this work, the CFD model, coupled to lithium ion

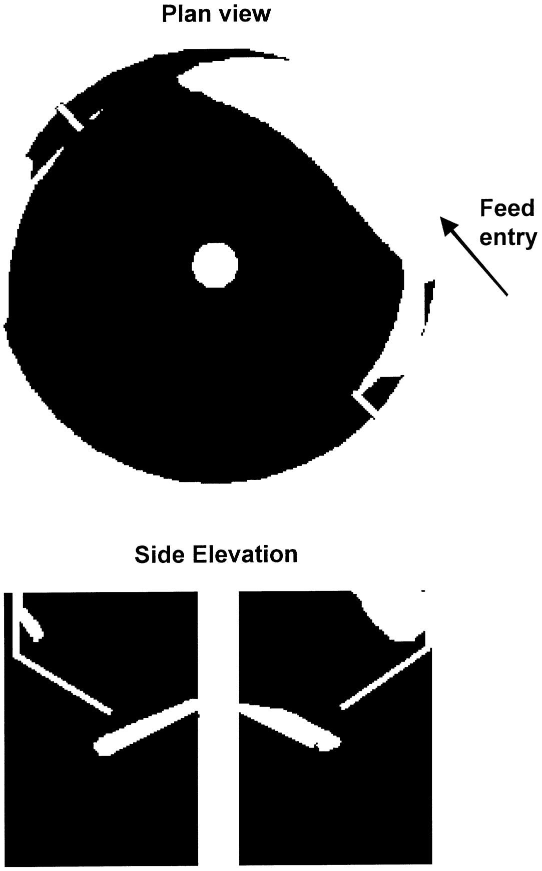

Fig. 10. CFD prediction of shear rate distribution within a full-scale feedwell. Lightest shade, highest shear; darkest shade, lowest shear.

tracer studies, provided a clear understanding of the flow patterns and flocculant performance requirements within Worsley's counter-current residue washing circuit. Based on this information, the flocculant sparge was relocated into a natural dilution stream entering at the base of the feedwell. This change resulted in more effective dilution of the flocculant prior to mixing with the bulk of the feed solids. The enhanced performance obtained through this modification, plus through changes to the design of the feedwell, doubled the throughput of the washer. This outcome reduced by three the number of new thickeners required for Worsley's recent expansion, saving millions in capital.

6. Rake operation and design

Rake design and operation is an important issue in thickener performance, but has received little attention in the literature. A study of individual rake components is under way to understand the basics of rake design. The approach involves small-scale physical experiments to complement CFD models. The physical experiments allow reliable data to be obtained for validating the CFD model, and also provide insights into the flow around rake components and

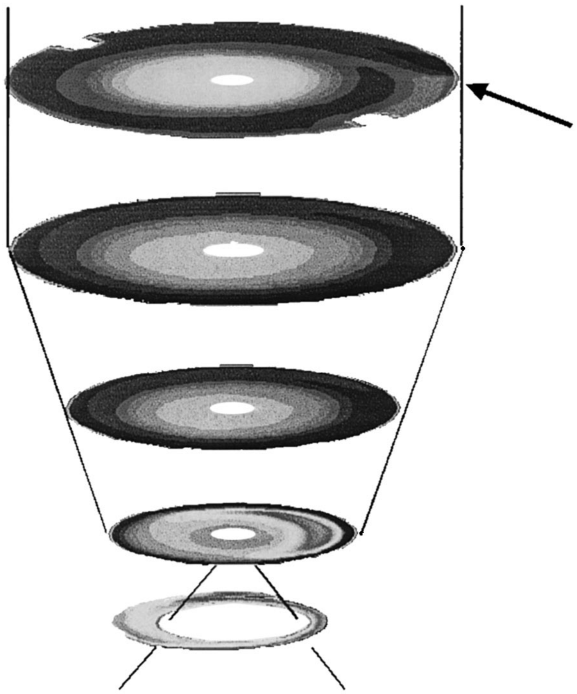

Fig. 11. CFD prediction of volume fraction solids (VFS) distribution in five horizontal planes within a full-scale feedwell. Lightest shade, lowest solids concentration; darkest shade, highest solids concentration. The recycling of clarified liquor into the feedwell is apparent in the bottom section. Feed inlet shown by an arrow.

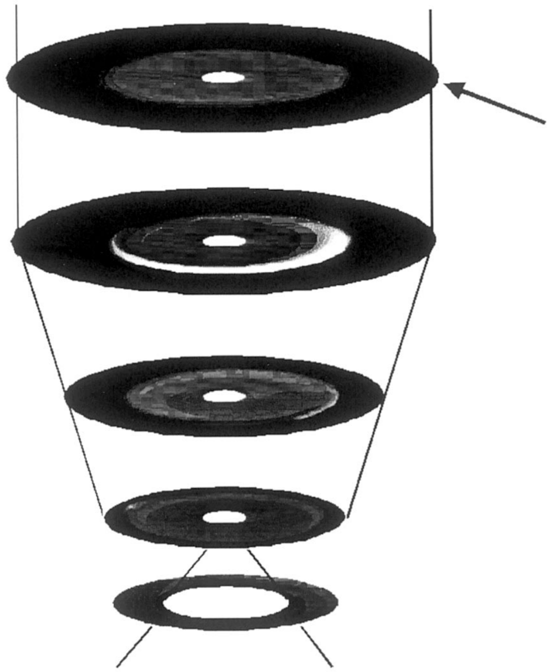

Fig. 12. CFD prediction of flocculant adsorption profile in five horizontal planes within a full-scale feedwell. Lightest shade, highest unadsorbed flocculant concentration; darkest shade, lowest unadsorbed flocculant concentration.

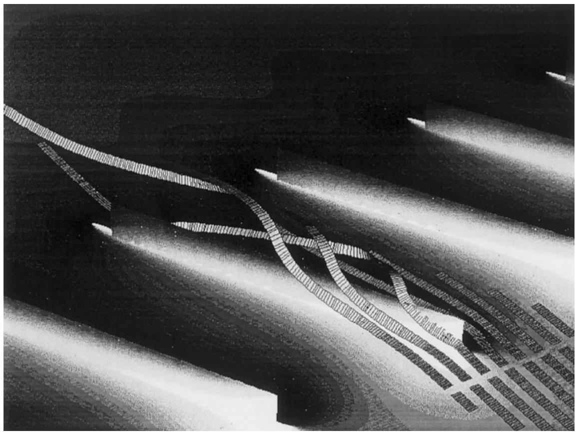

Fig. 13. CFD model prediction of ribbons of fluid moving across the surface of a series of rake blades.

structures that are not easily attainable from CFD. In the physical experiments, Carbopol solutions are used as model fluids to simulate the behaviour of underflow slurries (generally viscous, shear thinning fluids). Rheological aspects (such as thixotropy, compression, etc.) are neglected experimentally, but can be modelled computationally, thus extending the usefulness of the model beyond the simpler experiments. Eventually, this information will be used to assist in the design and implementation of a CFD model of complete rake structures for inclusion in the full thickener CFD model under development. An example of CFD modelling of flow induced by a series of rake blades (or rake blade 'cascade') is shown in Fig. 13.

7. Conclusions

Support from a wide range of mineral processing companies, thickener manufacturers and chemical suppliers for a series of research projects has resulted in new tools to address flocculation and thickening issues. These tools have identified how key factors (such as mixing intensity, mixing duration and solids concentration) affect flocculation efficiency and, hence, thickener performance. The development of a comprehensive CFD model has enabled prediction of full-scale performance under various process conditions, based upon a knowledge of thickener geometry, plant flows and laboratory assessment of the flocculation behaviour of the feed slurry.

Benefits of this research have already been obtained by sponsors, with the tools and techniques being used to identify better flocculant sparge locations and to evaluate the impact of engineering modifications to existing feedwells. However, further development is still required before the methodology to improve thickener performance will be sufficiently robust to accommodate the wide range of solid–liquid conditions encountered in the minerals industry.

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