

FROTHER AND COLLECTOR EFFECTS ON FLOTATION CELL HYDRODYNAMICS AND THEIR IMPLICATION ON CIRCUIT PERFORMANCE

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ABSTRACT

Significant progress has been made over the past few years on characterizing and understanding the hydrodynamic properties of frothers and collectors and their effect on flotation performance. This new understanding of the relationship between chemistry and hydrodynamics has dramatic implications for how flotation circuits should be controlled and optimized. Previous work has shown that choosing a frother of the right ‘strength’ is critical to the optimization process, and the work and discussion presented here serve to strengthen the argument. In addition, we know that collector chemistry will also influence hydrodynamic properties and needs to be taken into consideration. To achieve the desired outcome, the overall system of reagents and operating parameters must be considered. This paper describes and discusses some of the findings from recent research on frother and collector chemistry effects (on hydrodynamics), and how this knowledge can be used to improve flotation performance. Examples from plant experience are discussed.

INTRODUCTION

Frothers perform various functions in flotation but the primary ones are control of bubble size in the pulp zone and stabilization of the froth zone. Laskowski (1) was among the first to try to capture both roles in characterizing frothers in order to provide a basis for frother selection for a given duty, as well as to explore the link between function and frother chemistry (structure). The method he used requires bubble size data and a frothing index; the procedure has been simplified by Cappuccitti and Finch (2) using gas hold-up to substitute for bubble size, and froth height (without overflow) as the froth stability metric. The gas hold-up/froth height relationship will be referred to as 'hydrodynamic characterization'. Essentially, the gas hold-up parameter reflects the sum of the hydrodynamic conditions in the pulp phase (water in this case), i.e. the effect of bubble size plus the apparent impact of the water surrounding the bubble due to the frother (3). Similarly, the stable froth height parameter reflects the sum of hydrodynamic conditions in the froth, i.e. the effect of bubble size undergoing coalescence plus the influence of the water in the lamellae and Plateau borders between bubbles. It could be argued that the gas hold-up/froth height relationship is a superior one to simple bubble size/froth index for discerning differences in frother behaviour since it accounts for more complete hydrodynamic behaviour in both the pulp and froth.

Background

The test rig (Figure 1) is a laboratory column (height 425 cm, dia. 8 cm) instrumented to measure gas hold-up (ϵ_g , %) (using differential pressure) and control air rate (J_g , cm/s), with froth height recorded manually at steady state. Air is dispersed through a porous sparger. The system is run on air-water without solids. By testing a wide range of frother types it has been shown that each frother type exhibits a unique froth height vs. gas hold-up relationship (2). The relationship is established by fixing air velocity into the column ($J_g = 1.6$ cm/s at sparger, 1.92 cm/s at gas hold-up measurement) and running through a spectrum of frother concentration thus providing a range of froth height versus gas hold-up data. Typically, this means starting with concentrations well below the CCC (critical coalescence concentration) (1) increasing to well above the CCC. Each frother type will exhibit a unique CCC in its effect on reducing bubble size to a limiting value (1,4).

Figure 2 shows froth height versus gas hold-up for a selection of frother types, including the classics MIBC and Dowfroth 250, plus some Flottec products, indicating a wide range of responses from simple alcohol (MIBC) to polypropylene glycol (F-150). The trends are common: initially froth height increases slowly with gas hold-up then more rapidly, the change roughly corresponding to when the CCC for a particular frother is exceeded. The alcohols (such as MIBC) give relatively large change in gas hold-up with increasing frother concentration but little change in stable froth height in comparison to polyglycols (like F-150) that produce large change in froth stability for smaller change in gas hold-up. The relationships reflect the different water transport behavior of the frother types, with alcohols giving drier, less voluminous froths than the polyglycols (5,6,7). One outcome is that the performance of frothers is not solely dependent on concentration; i.e., it is not correct to assume that changes in concentration will make one frother perform like another. Bubble size in water (pulp) can be matched by changing concentration between 2 frother types (4) so that their relative concentrations to the CCC are the same, but gas hold-up and froth stability will be different.

It is also well established that some collectors possess frothing characteristics, such as fatty acids. What is not well understood is how collectors change bubble size or gas hold-up. Therefore, more research is required to understand the hydrodynamic characterization of collectors within the full reagent system.

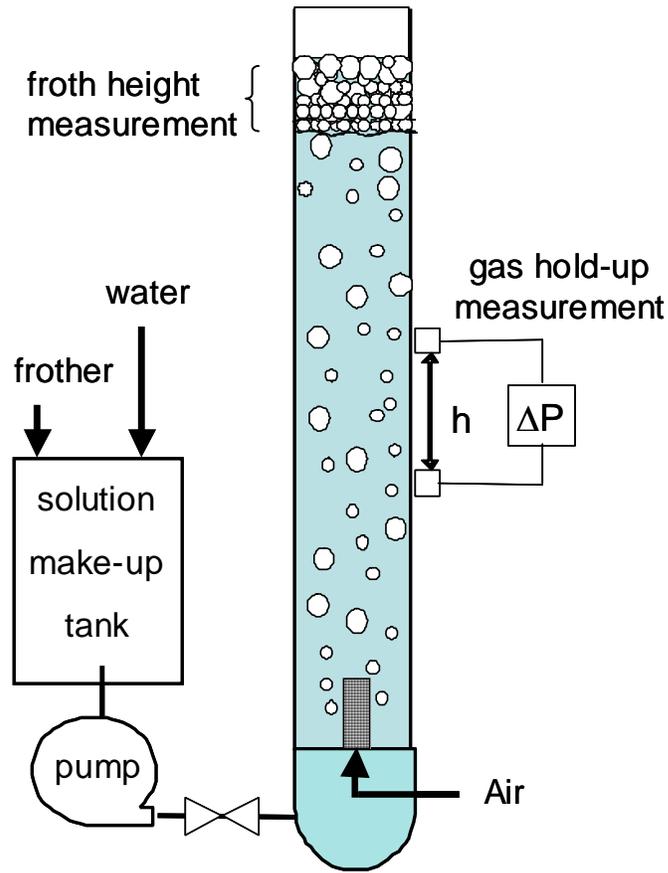


Figure 1 - The test rig used to generate froth height versus gas hold-up data

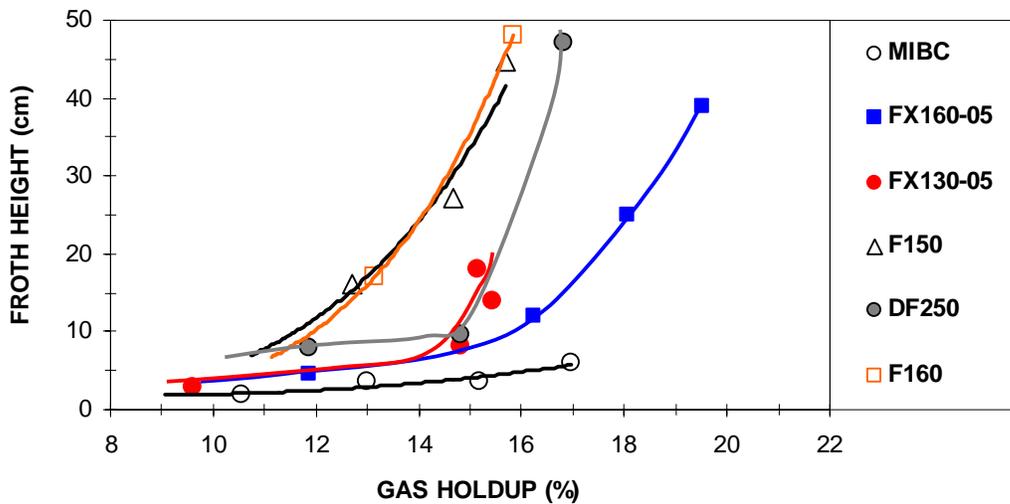


Figure 2 - Examples of froth height versus gas hold-up for a variety of frothers showing the wide range in response. MIBC methyl isobutyl carbinol, FX130-05 ethoxylated butanol, F-150 polypropylene glycol (PPG), DF250 PPG methyl ether, 160-05 PPG alkyl ether, 160 PPG butyl ether (gas rate, $J_g = 1.6 \text{ cm/s}$ at sparger)

FROTHER CHARACTERISTICS AND IMPLICATIONS ON FLOTATION PERFORMANCE

Now that there is better understanding of how frothers affect both pulp and froth properties, what is the implication on flotation optimization? Using Figure 2 as a basis, Figure 3 displays schematically what appears to happen in flotation when gas hold-up is changed by altering frother concentration (for fixed J_g). Two frothers that have widely different response are illustrated, MIBC and F-150. Gas hold-up increases as frother concentration is increased in response to decreasing bubble size; which in turn increases the bubble surface area flux, S_b , which directly increases flotation kinetics (higher mass flux). The opposite happens with decreasing frother concentration and gas hold-up. Therefore, as frother concentration-changes occur below the CCC, there is a significant change in flotation kinetics. The x-axis (gas hold-up) can be thought of as the 'gas pedal' in flotation and will reflect the combined influences of both frother and air rate.

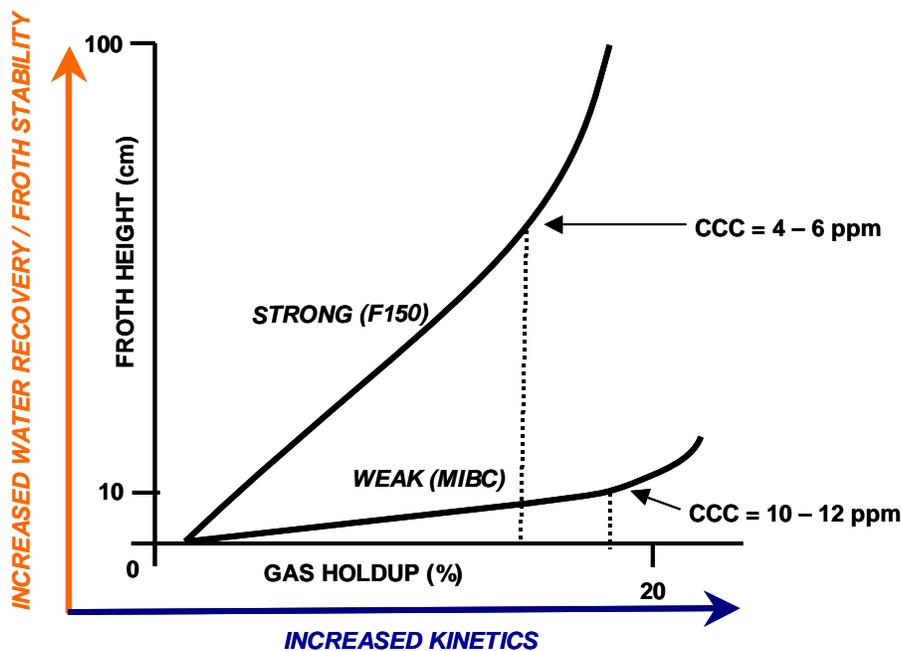


Figure 3 - Representation of link between hydrodynamic measurements and implication to flotation (gas hold-up to kinetics, and froth height to froth particle-holding capability)

The y-axis shows the froth stability (height or volume) as frother concentration is varied. As froth stability is altered, so its' ability to support solid particles also changes. The more stable the froth, the more it can be loaded with particles before collapsing under its own weight. This is due to the amount of water in the froth that stabilizes the bubbles (i.e. prevents coalescence) thus increasing the height or volume that can be supported. If the stability is insufficient, the froth cannot support the total mass of particles that are floated. This can occur with 'weak' frothers such as MIBC if kinetics and mass flux are high. Alternatively, if the froth is too stable (i.e. frother too 'strong' for what is required), this will lead to sub-optimal metallurgy (high entrainment) or downstream operational problems of froth persistence. In this sense, the water that accompanies the bubbles entering the froth can be thought of as temporary storage volume for the mass floated: If it is too small it becomes unstable, if it is too large it can cause performance problems of grade and persistence.

In hydrodynamic terms, a good frother must be a reagent that will give both the target bubble size reduction and adequate froth stability over a range of operating conditions. Frothers are often described as either 'strong' or 'weak'. In the past, this has been a qualitative description. Referring to Figure 3, we can now describe a 'strong' frother as one that produces large changes in stable froth height relative to gas hold-up, and a 'weak' frother as one that does the opposite. This definition remains somewhat arbitrary in that it does not link to frother concentration (ppm) directly, but the notion

that a significant slope change occurs at the CCC means that classification curves for frothers can be readily produced by conducting tests above and below the region of the frothers CCC. Operationally, frothers that are stronger will bring more water into the froth and hence be less selective due to increased entrainment.

FLOTATION CIRCUIT CONTROL

In most flotation circuits, keeping other variables (such as air rate and collector dosage) fixed, frother dosage (concentration) can be used to control the kinetics (mass removal rate). The fact that each frother type has a distinct relationship between froth stability (particle loading capability) and kinetics, means each frother will perform differently in a circuit. This implies that there is a specific frother (having a specific hydrodynamic characteristic) that will best balance mass pull (kinetics) and froth stability (loading). The following scenarios illustrate this.

Frother Too Weak for the Circuit

The condition is a collapsing froth due to too heavy a mineral load, frother concentration is below the CCC. The operator increases the frother addition rate. This in turn increases kinetics and more mass is pulled into the froth. The froth stability is not increased significantly and the collapsing of the froth is exacerbated. Therefore, if the frother is too weak, adding more in this situation simply makes the problem worse.

Frother Too Strong for the Circuit

The tail in a flotation circuit is high. The operator wants to increase the mass pull and increases the frother dosage to increase kinetics. The froth persistency and volume is increased significantly but the mass pull is not. The more persistent, voluminous froth causes grade to drop and there are operational problems with frothing downstream. The frother may be too strong for this circuit.

It is important to find the frother with the appropriate strength that will provide the optimum control in each flotation circuit across a useful range of dosages and ore conditions. Understanding flotation cell hydrodynamics, how they can be affected by frothers and other operating parameters, and what hydrodynamic conditions exist in the circuit can assist greatly in making adjustments to improve metallurgical performance (8,9,10,11,12).

DISCUSSION: IMPLICATIONS OF REAGENT EFFECTS ON CELL HYDRODYNAMICS AND FLOTATION CIRCUIT PERFORMANCE

Frother Addition Rates and Concentration in the Flotation Pulp

It has been established (4) that bubble size (nominally D_b , or the Sauter mean size, D_{32}) in the pulp phase is directly related to the ppm concentration of frother in the aqueous phase of the pulp (Figure 4a) and that the CCC for a given frother will increase with air rate J_g as modeled by Nasset (13). Knowledge of the CCC (critical coalescence concentration) for a particular frother establishes what concentration is required to give minimum bubble size (1, 3) and hence maximum S_b . We also know that the shape of the curve that defines the relationship between froth creation and bubble size reduction at various concentrations is unique for each frother type (7).

Realizing that frother functions in the aqueous phase means that addition to the circuit should be controlled by the ppm concentration in the water phase as opposed to the g/t of ore or metal value in the circuit feed. It is understood that g/t (ore or metal basis) of frother is related to the ppm by the % water of the pulp, and hence the actual ppm in solution is an *a posteriori* calculation rather than a desired set point, since the tonnage and ratio of solids-to-water may fluctuate. Conceptually, adding sufficient frother to minimize the bubble size at a given air rate provides maximum bubble surface area flux (S_b) and, hence, flotation kinetics. Unless there is an expressed reason for not wanting the minimum bubble size, the frother concentration in the pulp should be kept close to the CCC of the frother (Figure 4b) (13). This optimum frother concentration will increase with air rate as illustrated in Figure 4b (for Dowfroth 250), an important consideration for circuits where J_g may vary down a bank of cells. Since frother may deplete in the pulp going down a bank, due either to concentrating into the froth phase or volatilizing with air from the cell, stage addition may be required to maintain the frother at the required CCC level. Volatile frothers such as alcohols (MIBC) are more susceptible to depletion than glycol based products. Failure to maintain the frother concentration will result in increased bubble size, loss of flotation kinetics and decreased mineral recovery, often at the point in the circuit where the more difficult mineral components (fines,

coarse, composites) are being recovered. Some plants counter this problem by adding weak frothers at levels exceeding the CCC to avoid falling below the CCC when downstream conditions change. The detrimental impact to operating cost, froth quality and downstream circuits is obvious. Table 1 lists the CCC95 values (the frother concentration for which D_{32} has decreased by 95% of the full amount possible) (4) for 5 different frother types at two levels of J_g .

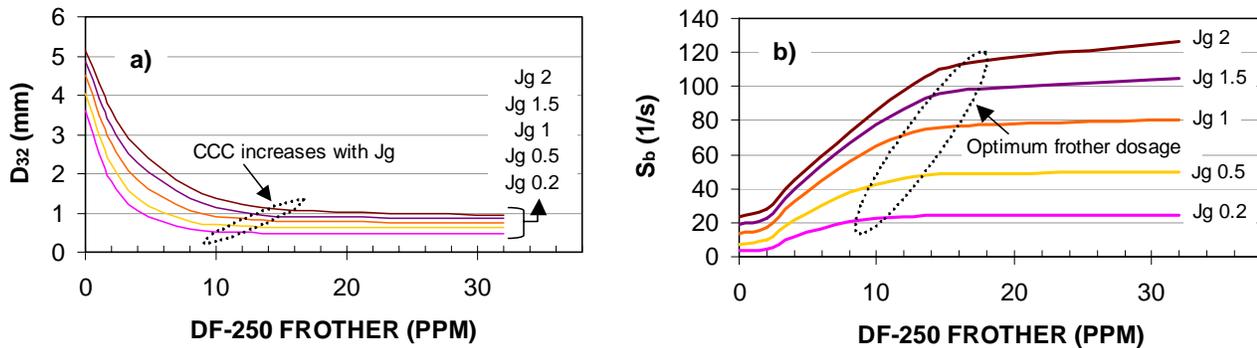


Figure 4 – a) Bubble size (D_{32}) reduction with increasing frother dosage showing how CCC increases with J_g
 b) Effect of frother dosage on bubble surface area flux (S_b) showing optimum dosage increasing with J_g

Table 1 – CCC95 Values for Various Frothers at Two Values of J_g

Frother	CCC95 (ppm)		
	$J_g=0.5$	$J_g=1$	Average
Pentanol	25.59	34.03	29.81
MIBC	10.45	12.47	11.46
D-250	8.35	13.86	11.11
F-140	7.66	11.48	9.57
F-150	3.74	5.26	4.50

Choice of Frother to Use in a Circuit

As discussed, the optimum frother provides a balance between kinetics and froth stability over the control range of addition. Usually, one frother is used to achieve this. But using one frother gives only one unique hydrodynamic relationship. Ideally, it would be desirable to have independent control of bubble size and froth stability. Unfortunately, this cannot yet be achieved because changing the concentration of the frother changes both variables.

An alternative strategy for gaining more independent control over froth characteristics and bubble size would be to use a dual frother system, likely a strong and weak frother added independently. Such a system would give an additional degree of freedom in that changing the ratio of the two frothers would shift the resulting hydrodynamic curve and, hence, the response of the circuit. This would provide more independent control of D_b , ϵ_g , S_b and froth stability.

The advantage of using a single frother is simplicity in an already complex system. If the circuit has somewhat low variability and non-complex flotation, the use of a single frother would be recommended. The advantage of a dual frother system is more flexibility in highly variable and complex circuits. For example, changing the frother ratio (weak/strong, added independently) down the flotation bank. The use of more weak/less strong frother early, followed by stronger frother later in the bank would increase optimization possibilities for recovering fines, intermediates and minimizing entrainment of gangue. A dual frother system could be more cost effective since strong frothers normally function at lower dosages.

Collector (and other reagent) Effects on Cell Hydrodynamics

Collectors, like frothers, are surface-active agents and therefore are likely to exhibit hydrodynamic characteristics. Collectors are termed to be ‘frothy’ (froth positive), neutral or froth negative. It is not desirable that collectors have a strong froth characteristic because independent control of hydrophobicity and hydrodynamics is preferable. As an example, the amount of froth-positive collector added may need to be limited to less than optimum because it creates excess froth. To date, there has not been much research on the hydrodynamic characterization of collectors or collector/frother systems. It is not well understood whether collectors that exhibit froth characteristics are also effective bubble size reducers. If collectors have minimal effect on D_b , the implications would be very significant for flotation systems where the froth creation comes primarily (or completely) from the collector, such as fatty acid or amine flotation.

Figure 5 shows the hydrodynamic response of a collector, DPG 25, (as well as several frothers for reference) which is used alone in a flotation circuit without a frother, at dosage levels typical of operation. The figure clearly shows that the collector provides small froth height but does not reduce bubble size (since gas hold-up remains unchanged). In fact, it is also poor at stabilizing the froth, possibly due to low water recovery into the froth. These results illustrate the point that this circuit could benefit from the use of a frother that would stabilize the froth, lower the usage of collector, and provide metallurgical benefit by reducing bubble size. Plant tests did confirm that when frother was added, collector levels decreased significantly and metallurgical improvements were indicated.

The implications of these findings are that in circuits, such as industrial minerals, where collectors currently provide the froth, the added use of a frother to specifically control bubble size may be beneficial. Weaker frothers may be called for so that the froth is not excessively stabilized if it is already strongly so by solids or other considerations such as as high salt content (14,15). The call is for further work to determine the hydrodynamic characteristics of collectors and, indeed, entire reagents systems, not just frothers, since what is of interest in a cell is the total of all reagent interactions.

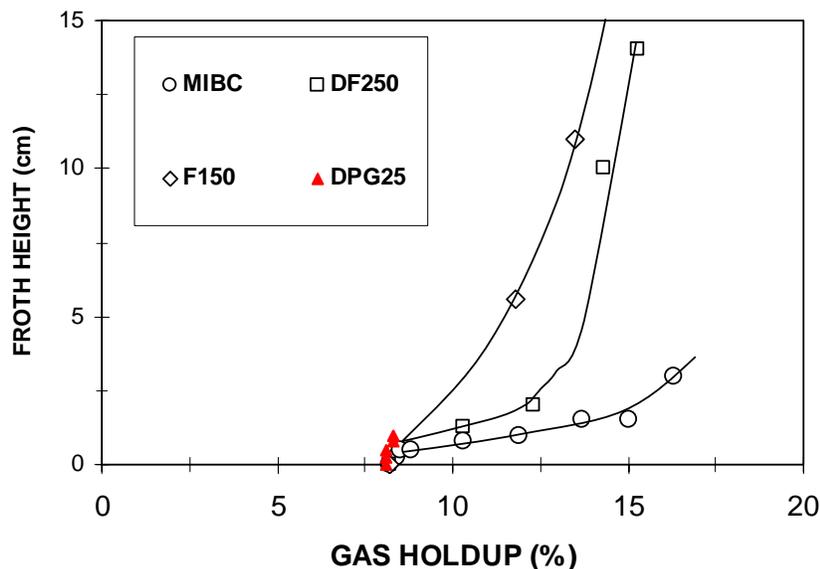


Figure 5 - Gas hold-up versus froth height for 3 typical frothers and one collector, DPG 25, which was used without frother in the flotation circuit

Controlling Bubble Size Distribution (Population) in a Circuit

The bubble size distribution (BSD), or population of bubbles in a cell, is dependent on the frother type and concentration, J_g , bubble generation system (e.g. mechanical agitator, jetting sparger, in-line mixer), viscosity and other factors (4). The effect of frother concentration alone (4) is illustrated in Figure 6 showing that increasing frother dosage not only decreases the bubble size parameter, D_{32} , but also dramatically alters the shape of the BSD, which becomes narrower and less bi-modal as dosage is increased. By manipulating key variables, we have some control over the BSD in a cell and, in theory, the optimum match between the BSD and the particle size distribution can be produced. In essence,

smaller particles will be more efficiently collected by smaller bubbles and coarser particles by larger bubbles. This is a large oversimplification but serves the purpose of this discussion. A good review is provided by Jameson, Nguyen and Ata (16). Nasset et al (11) and Hernandez et al (8) showed that lack of minus 1mm bubbles in a rougher/scavenger bank resulted in poor recovery of minus 10-micron Pd particles at a plant using a weak frother (MIBC) below the CCC. Adding a strong (poly-glycol) frother in the final cells of the bank resulted in a marked shift of the BSD to below 1 mm, and a dramatic increase in minus 10-micron particle recovery.

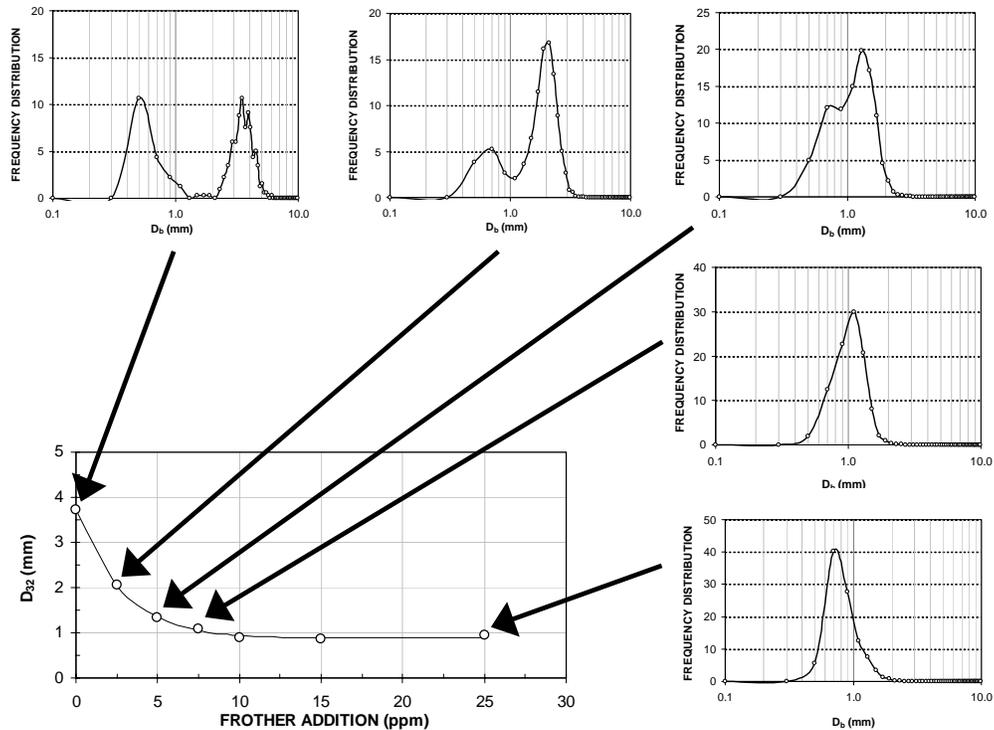


Figure 6 – How the bubble size distribution changes as frother concentration is increased (Dowfroth 250)

To manipulate bubble size, the two most practical variables are frother concentration and air rate. Nasset et al (4) have shown that D_{32} increases as the square root of J_g so, although effective, the manipulation of bubble size by frother is more responsive. Figure 7 illustrates the trade-off between frother concentration and J_g for D_{32} and S_b (the example is for Dowfroth 250). This “road-map” shows that most plants tested to date (4) do not operate at their CCC levels indicating considerable room for manipulation of bubble size as an optimization strategy. A standard approach to analyzing circuit performance is to look at the losses of valuable minerals by particle size in the tails, and establishing if they predominate in the coarser or in the finer fractions. A portion of the circuit can then be set-up to improve recovery of the lost fractions. As in the example cited above, increasing frother concentration down a bank would produce smaller bubbles (until the CCC is reached) for a given air rate, and favour recovery of the finer fractions. Leaving the frother concentration the same and increasing air rate down the bank would serve to increase bubble size favouring recovery of coarser material. Understanding the relationships between bubble size, frother and air rate also opens other possible scenarios for matching the BSD to specific particle size recovery, viz: to increase bubble size

- a) Dilute the circuit (or portion) with water resulting in a lower frother concentration
- b) Use a frother that is more readily stripped (volatile) from the pulp
- c) Rather than a), add water only to the bubble formation zone in the target cell(s)

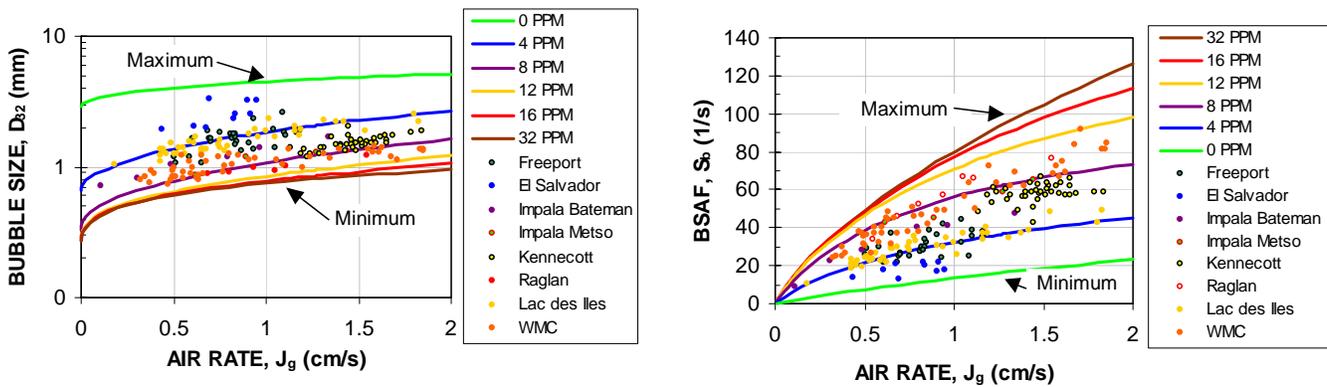


Figure 7 – Relationships between air rate (J_g) and bubble size (D_{32}) on left, and air rate and bubble surface area flux (S_b) on right. The frother concentration curves are for Dowfroth-250. The indicated minimum (0 ppm) and maximum (far exceeding the CCC) are the same for all frothers. These ‘road maps’ serve to indicate the potential for improvement

Froth Stability, Water Recovery and Mass Flux (flotation kinetics)

Flotation recovery may be described as a first order rate equation where Recovery (R) at any given time is related to the ultimate Recovery (R_∞) and the rate constant (k) that describes the speed (kinetics) of material removal. This R_∞/k trade-off has been described in articles by Klimpel (17). Figure 8 shows several possible time-recovery plots that can result from changing the rate (k) at which the mass is recovered (mass flux) as well as R_∞ . Understanding the hydrodynamics of the system may aid in interpreting what is happening. Water recovery is a key feature of frothers related to their hydrodynamic characterization. Each frother type tends to give different water recovery rates (7). Recent work by Zhang et al (18) describes a method for determining an equivalent water thickness associated with the S_b exiting via the froth overflow. This equivalent thickness is a quantitative method for characterizing the frother types, giving similar rankings to the hydrodynamic characterization method described here. The mechanism is not clearly understood but as an aid to discussion frothers can be considered to function by creating a film of water around the bubble. A stronger frother creates a thicker film and weaker frothers create a thinner film. As the film thickness changes, so does the water recovery to the froth. In this way a frother will create a foam stabilized by the presence of water; in flotation particles take on some of this role to create a stabilized froth (15). As mass flux to the froth decreases down a bank of cells, it is often more difficult to create a stable froth. The less stable the froth, the harder it is to get recovery. Adding more frother may create more froth and water recovery, but may not create more true flotation recovery due to insufficient mass required to create a stabilized froth.

The notion of a water film on the bubble introduces the hypothesis that the thickness of the film can also affect the flotation of coarse versus fine particles. A particle must penetrate the water film layer in order to attach to the bubble. The induction time is the time required for that attachment. If the contact time of the particle is greater than the induction time, the particle will attach. If the water film is thick, a fine particle may not have the momentum to penetrate the layer and attach (16). If the water layer is thin, there may be too much turbulence near the interface to keep a coarse particle attached. Therefore high water recovery tends to favor coarse particles and low water recovery tends to favor fine particles. This may be why weak frothers are often referred to as selective (favor grade by rejecting coarse intermediates and having low entrainment) and strong frothers as persistent (favor recovery as they float more coarse and have higher entrainment).

Through better understanding of the impact of frother selection on hydrodynamics, it is possible to suggest different strategies for improving circuit performance. For example, what can be done in a circuit that has poor recovery yet the last cell or cells in the rougher/scavenger circuit have little to no recovery? In this case, due to very low mass flux in these final cells, there is no stable froth to recover. In order to stabilize the froth at the back end of the circuit, the front end could be slowed down and mass recovery moved further down to produce a stable recoverable froth. This would mean deliberately lowering the k value to get an improved R_∞ . The second scenario in Figure 8 illustrates this. If recovery losses were largely confined to either the fine or coarse fractions, the use of specific frothers may be warranted. To improve fine particle recovery, the use of a high concentration (at the CCC) of a weak frother added to the final cells would ensure that the bubble size is at a minimum which would give you the best hydrodynamic conditions for fine

particle recovery. To improve coarse particle recovery, the addition of a strong frother at the end of the circuit would improve water recovery and favor coarse particle flotation. The 3rd scenario in Figure 8 illustrates this situation.

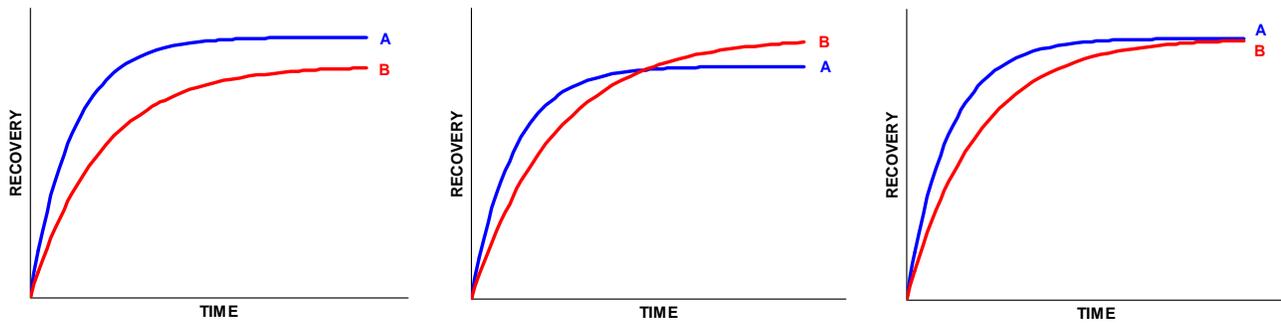


Figure 8 – Time- recovery curves for 3 flotation systems having different R_{∞}/k values. In the first system, B has lower k and R_{∞} (may have different hydrodynamic conditions). In the second system, A has a higher k value but lower overall R_{∞} than B. System 3 has different k values but the same final R_{∞} .

On-line Gas Hold-up Measurement

Much of the research and development work done to date on understanding flotation cell hydrodynamics and gas dispersion parameters in a plant has involved the use of portable gas hold-up (ϵ_g), bubble size (D_b) and air velocity (J_g) sensors (19). These sensors are put in place to gather data over short periods of time and have provided excellent information on where a plant operates relative to these parameters (Figure 7). The sensors have also provided the data that has been required to better understand the relationships between the reagent chemistry and the operating parameters.

The next logical step would be to determine if on-line real time measurement of gas dispersion parameters would provide better flotation circuit control. Bartolacci et al (20) have reported some initial success with column control. As an example, gas hold-up may be a practical substitute for bubble surface area flux and hence a fundamental driver of performance. Gas hold-up reflects the sum total of the operating conditions of the cell and will depend on the bubble size, the air rate, the condition and geometry of the equipment, the rheology and chemistry of the pulp, and the type and amount of reagents added. Some of these factors are fixed, some change gradually over time while others will result in immediate changes in the performance in the circuit. Much of the work done to date suggests that there may be a discrete point or narrow range of gas hold-up that will result in the optimum performance of a cell. This has not been firmly established because, up to this point, reliable on-line measurement of gas hold-up has not been available. Today, there are newer technologies that make on-line gas hold-up measurement possible (19,21). Research is required to determine if and how gas hold-up could be linked as a control strategy to hydrodynamics and flotation circuit optimization.

CONCLUDING REMARKS

We have presented a discussion paper and introduced a method of characterizing the hydrodynamic properties of frothers using froth height (as a measure of froth stability) versus gas hold-up (as a combined measure of bubble size in the pulp and water film thickness on the bubble). Frother types exhibit different hydrodynamic characteristics and this helps distinguish frothers considered ‘weak’ from those considered ‘strong’. Frother addition should be controlled by considering the concentration in the aqueous phase as opposed to the feed rate of ore or metal. The critical coalescence concentration (CCC) concept is a useful one for assessing circuit performance and the potential for improved recovery. Blended frothers may offer some independence over the froth and bubble size control functions. In addition to frothers, other reagents, such as collectors, may also possess hydrodynamic properties and the combined characteristics of all reagents added needs to be considered. An appreciation of the difference in water-carrying rate between weak and strong frothers will permit the metallurgist to better select a frother-addition optimization strategy for recovery of fine and coarse particles that would otherwise be lost to tails. It is also suggested that on-line measurement of gas hold-up could be useful for optimizing mass flux. Frothers clearly have the potential to be one of the most useful variables for exploitation in a flotation circuit. It is hoped that this communication will aid in this regard.

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