CHAPTER 16

THE DYNAMIC BEHAVIOUR OF COARSE PARTICLES IN FLOTATION FROTHS

W.A. VAN DYK, J.S.J. VAN DEVENTER, AND L. LORENZEN
DEPARTMENT OF CHEMICAL ENGINEERING, UNIVERSITY OF STELLENBOSCH,
STELLENBOSCH, 7600, SOUTH AFRICA

ABSTRACT

Hydrophobic particles with diameters between 1 and 3 mm are poorly recovered by conventional flotation techniques. A novel reverse flotation technique is described whereby coarse particles with surfaces rendered highly hydrophobic, repel the bubble films in a froth and thus drop through the froth under gravity, to be recovered as a sink product. Conversely, gangue or hydrophilic particles are supported by the bubble films in the froth and are therefore recovered as a floating product.

Tracer tests were conducted in the cell in order to study the dynamic behaviour of solid particles in the froth. The effects of hydrophobicity, density, particle size and particle shape were investigated experimentally. The higher the hydrophobicity of the particles, the lower the recovery of particles as a floating product, while the recovery of particles as a sink product increases with an increase in particle density. Furthermore, a decrease in particle size results in an increase recovery of hydrophobic particles as a floating product. When treating particles of the same mass-to-surface-area ratio in the froth, flat particles would be recovered as a floating product in preference to cubic, disc-shaped, cylindrical and spherical particles, in that order.

INTRODUCTION

The early recovery of coarse valuable material from a mineral processing circuit could have numerous advantages, such as preventing over-grinding of minerals, reducing conventional flotation time and increasing the recovery of valuable materials. Several researchers have therefore ventured into this field, proposing new techniques, processing circuits and/or alternative flotation reagents.

A system was proposed by Lloyd (1987) in which gold and other valuable minerals could be concentrated underground by coarse milling and flotation. A model of the process, however, indicated that the flotation step would be able to recover only 75 percent of the valuable minerals due to large losses in the coarser particle size ranges. Schubert (1989) investigated the development of an impeller type and impeller-stator flotation system that would recover coarse particles in the treatment of quartz sands and sylvanite. The major criterion that had to be satisfied in this regard was that the coarse particles had to be suspended but not agitated to such an extent that would impose unnecessary turbulent stresses on the bubble-particle aggregates. The design resulted in a lower power consumption but, although it appeared successful for particle sizes of up to 0.4 mm, difficulties were encountered at the coarser size ranges. Other studies were aimed at the use of alternative flotation reagents to improve the yield of coarse coal particles but with limited success (Moxon and Keast-Jones, 1986); (Moxon, Keast-Jones and Aston, 1988).

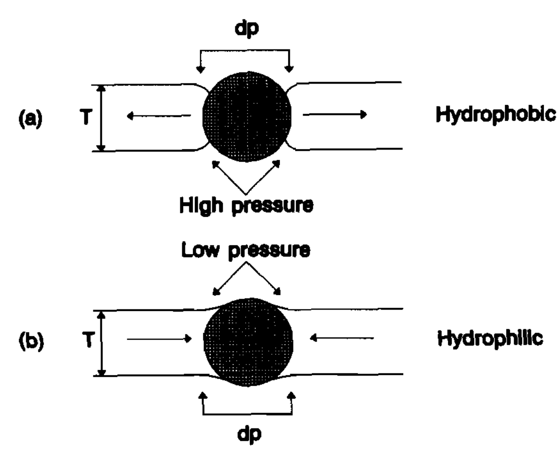
These investigations have shown that a need exists for a coarse particle separation technique with low operating costs, such as a low power consumption and relatively inexpensive flotation reagents. A technique was developed (Ross, 1993) whereby coarse particles with highly hydrophobic surfaces repel the bubble films in a froth and thus drop through the froth under gravity, to be recovered as a sink product. Conversely, gangue or hydrophilic particles are supported by the bubble films in the froth and are therefore recovered as a floating product.

THEORY

Rupture of bubble films

In a study on the interaction of a solid with a thin liquid film, Dippenaar (1982) found that moderately hydrophobic particles can be transformed into very effective film-breakers if they are coated with a reagent that produces a static contact angle of more than 90° on the solid. When such a particle is introduced into a lamellar froth, the instantaneous contact angle formed at the newly developed three-phase boundary is much smaller than the equilibrium contact angle. The movement of the three-phase boundary over the particle to attain an equilibrium contact angle causes the bubble film to thin and rupture when a critical bubble film thickness is reached. The process of bubble film thinning and rupture occurs in a few milliseconds and could be applied in the selective recovery of highly hydrophobic particles if the right froth conditions are maintained.

Figure 1. Spherical Particle Protruding Through Both Sides of a Bubble Film and the Capillary Pressure-driven Flow Mechanism of Bubble Film Rupture.



Hemmings (1981) postulated a protruding particle theory to explain the effect of hydrophobic particles with diameters greater than the thickness of the supporting liquid films on flotation froth stability. The basis of this theory is a quantification of the tensile and compressive stresses caused by particles protruding through the bubble films. Figure 1(a) gives a schematic representation of a spherical particle protruding through both sides of a bubble film. Interfacial forces tend to cause the particle to protrude further into the gas phase on each side of the film if

$$\cos\Theta < \frac{T}{d_p} < \cos\frac{\Theta}{2} \qquad (1)$$

where Θ is the contact angle, T is the bubble film thickness (mm) and d_p is the particle diameter (mm). The equal and opposite reaction to this interfacial force is a destructive compressive stress that promotes film thinning and therefore is a latent cause of froth instability. Interfacial forces tend to cause the particle to submerge itself in the liquid on both sides of the film if

$$0 < \frac{T}{d_p} < \cos\Theta \qquad (2)$$

The equal and opposite reaction to this is a supportive tensile stress that tends to prevent film thinning. From equations (1) and (2) it is obvious that no region of supportive tensile stress exists for $\Theta >$ 90°, which means that a large particle with a contact angle of more than 90°, will cause bubble film thinning and rupture.

Frye and Berg (1989) proposed a mechanism for particle-induced film rupture and performed a hydrodynamic analysis to determine criteria for effective antifoam action by solid particles. They assumed that the mechanism that causes bubble film thinning or stabilisation is driven by capillary pressure. As shown in Figure 1, a coarse particle will bridge the film upon entering the froth, and curvature of the air-water interface will occur in order to satisfy the contact angle requirements at both interfaces. This curvature will result in local pressure variations, the magnitude of which is determined by the Young-Laplace equation::

$$\Delta P = \sigma\left(\frac{1}{R_1} + \frac{1}{R_2}\right) \qquad (3)$$

where ΔP is the pressure drop across the interface, σ is the surface tension and R_1 and R_2 are the principal radii of curvature of the surface. The sign of the pressure drop is determined by the direction of the interface curvature, which in turn depends on the contact angle (Figure 1 (a&b)).

Particle and froth characteristics

The capillary pressure-driven flow, and therefore film thinning, depends on the contact angle as discussed above. However, the total dynamic behaviour of the particles in the froth depends on a number of additional particle and froth characteristics. Density, shape, surface characteristics (hydrophobicity or hydrophilicity, and roughness) and size are important particle characteristics, while the bubble size, residence time of the bubbles in the flotation cell and the rigidity and thickness of the bubble films, in turn, are important froth characteristics. A particle in the froth is surrounded by a number of bubbles. Although the particle is not immersed in the film to the same degree as assumed by Dippenaar (1982), Hemmings (1981) and Frye & Berg (1989), the same principles of bubble film stability and film rupturing action would apply at each point where the film and the particle is in contact.

The structure of the froth is another important factor in determining the extent to which particles of various sizes, shapes and hydrophobicities can rupture bubble films. The size of the bubbles increases with increasing height above the froth interface due to bubble coalescence, a decreased hydrostatic head, and froth drainage. The structure of the froth changes accordingly from (a) a bubble swarm at the interface to (b) a packed bubble bed in the intermediate region to (c) a polyhedral structure at the surface. The polyhedral bubble structure is characterised by the fact that the bubbles are separated by rigid liquid films rather than existing as individual mobile entities at the interface, and it is under these conditions that the mechanism of film thinning is most effective. This suggests that the feed particles should therefore be introduced onto the froth surface to maximise the efficiency of the separation.

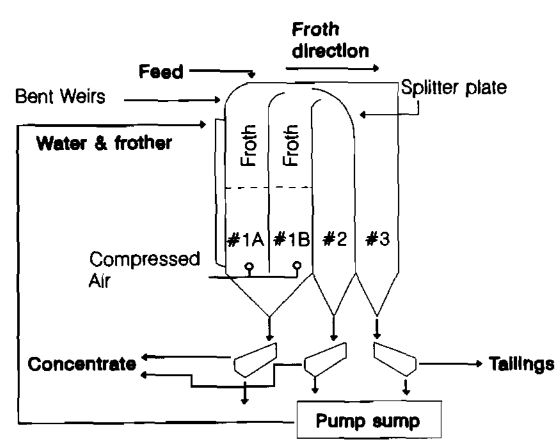
The stability of a froth is directly related to the stability of the liquid lamellae. As mentioned above, the size of the bubbles in the froth increases with increasing height above the froth-liquid interface. The froth becomes more rigid but less stable with increasing height above the interface, and therefore affects the flotation of particles of various surface characteristics and shapes. This suggests that there is an optimum water-to-air ratio for each particular bubble size for the flotation of particles with a specific hydrophobicity and size. The addition of frothing agents that increase the rigidity of the bubble films would increase the ability of the liquid lamella to support particles in the froth. The water-to-air ratio can therefore be regulated to a large extent by the addition of a frothing agent to the water.

EXPERIMENTAL

Flotation cell

The original concept, where particles are fed from the top onto a horizontally flowing froth bed, was described by Ross (1993). Various alterations were made to this design in order to minimize froth disturbances. The laboratory-scale flotation cell is illustrated in Figure 2. The cell consists of three tanks arranged alongside one another. To enable the settling of coarse hydrophobic particles through the froth, the vertical velocity component of the bubbles is kept as small as possible by bent weirs forcing the froth in a horizontal direction. The froth is formed in the first tank from where it moves

Figure 2. Schematic Representation of the Flotation Cell.



horizontally towards the second tank. A splitter plate splits the body of froth into upper and lower froth streams. Aeration of the cell is obtained by compressed air through porous Teflon air-spargers in compartments #1A and #1B.

The hydrophilic particles are supported by the bubble films in the froth and are carried over to compartment #3 while the hydrophobic particles break the bubble films and report as a sink product in compartment #1 and compartment #2. The particles are fed by hand onto the froth or by a vibratory feeder which can be installed. The particles are separated from the aqueous phase by screens at the discharge points of compartments #1, #2 and #3, from where the aqueous phase is recycled, via the pump sump, to the buffer tank.

Materials and methods

Density tracers of various specific gravities and shapes were manufactured and used in the testwork. The tracers were coated with candle wax as the coating is stable and easy to apply. The fresh wax is in addition inherently hydrophobic and yields an equilibrium contact angle of 98°. The contact angles were measured by the sessile drop method. However, it was found that the results could not be reproduced as the hydrophobic wax coating seemed to become increasingly hydrophilic with time when soaked in water (the static contact angle reduced to < 40° after 48 hours of soaking). This is in accordance with observations by Adam (1944) on factors modifying contact angles. While this was at first seen as a drawback, it was realised that this property could be very useful to quantify the hydrophobicity in terms of the flotation behaviour of small tracers. However, the above mentioned work is beyond the scope of this paper. The soaking time of the wax-coated tracers is therefore taken as a measure of the particle wettability.

RESULTS AND DISCUSSION

Behaviour of particles in novel cell

All the tests were conducted at an aqueous phase temperature of 25°C, pH of 7, a frother dosage of 1500 ppm Montan LIC40 and spargers with aperture = 50 μm. A further 4200 ppm xanthate was added to the frothing agent to enhance the bubble film stability as well as 2 drops of Teepol/33/ demineralized water. The relevant tendencies are explained in view of the graphs for the recovery of particles to the tailings. The total soaking time of the particles in the aqueous phase (measure of the particle wettability) is plotted on the x-axis, while the percentage of particles reporting to the tailings is plotted on the y-axis.

The effect of particle density is illustrated in Figure 3. Cylindrical tracers with an average length and diameter of 3.38mm and 2.08 mm respectively, and specific gravities of 3.50, 3.10, 2.90 and 2.70 were used in conjunction with an aeration rate yielding superficial gas velocities of 8.9 mm/sec in compartment #1A and 8.9 mm/sec in compartment #1B. As expected, an increased density results in a decreased recovery to the tailings, as can be seen in the S-shaped curve shifting towards the right on the graph of recovery to the tailings. This is expected since the gravitational force on the particles increases while the area available for support by the bubble films remains constant. The particle would thus drop through the froth under the influence of gravity. (Table 1 gives the mass-to-surface-area ratios (M/A) for the various particles).

Figure 3. The Effect of Particle Wettability and Density on the Recovery of Cylindrical Tracers to the Tailings.

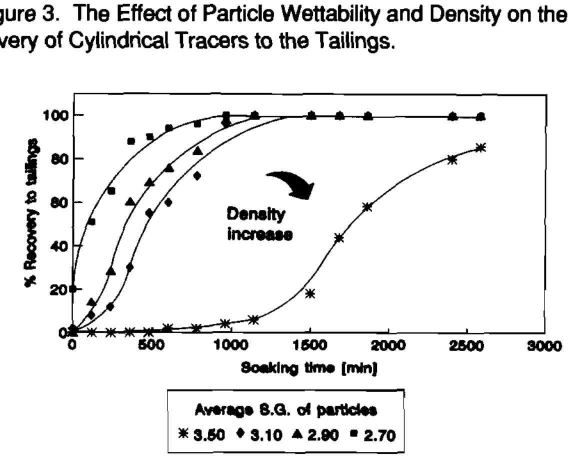
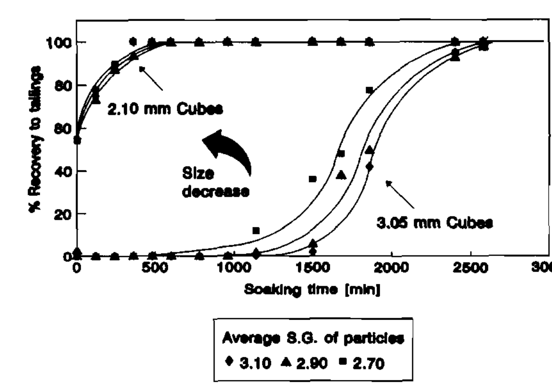


Table 1. Applicable Data of Density Tracers.

Shape	Dimensions [mm]	SG	M/A Ratio
cube	3.05 side	3.1	1.58
cube	3.05 side	2.9	1.47
cube	3.05 side	2.7	1.37
cube	2.1 side	3.5	1.23
cube	2.1 side	3.3	1.16
cube	2.1 side	3.1	1.09
cube	2.1 side	2.9	1.02
cube	2.1 side	2.7	0.95
disc	2.08 * 1.98	3.5	1.19
disc	2.08 * 1.98	2.9	0.99
cyl	2.08 * 3.38	3.5	1.39
cyl	2.08 * 3.38	3.1	1.23
cyl	2.08 * 3.38	2.9	1.15
cyl	2.08 * 3.38	2.7	1.07

Figure 4. The Effect of Particle Size on the Recovery of the Cubic Particles to the Tailings.



However, it is also evident from Figure 3 that the hydrophilicity of the particles affects their recoveries significantly. With an increased soaking time of the coated tracers in water prior to flotation, their hydrophilicity increases and this results in an increased recovery of these particles to the tailings. The increased wettability of the particles improves their bubble stabilising properties and they are more readily supported by the bubble films, an observation that correlates with the film rupturing theory of Hemmings (1981). It is also evident that, the larger the M/A ratio of the particles, the longer the soaking time that is required to improve their wettability to such an extent that they can be recovered in the tailings.

The influence of particle size on the recovery of particles is depicted in Figure 4. Cubical particles with side lengths of 2.10mm and 3.05mm respectively were used. Tests were conducted using tracers of three specific gravities (3.10, 2.90 and 2.70) and an aeration rate yielding superficial gas velocities of 8.9 mm/sec for compartment #1A and 8.9 mm/sec for compartment #1B. Similar trends are observed as for the cylindrical tracers in Figure 3, viz the recovery to the tailings decreases with an increase in particle size as portrayed in the S-shaped curves shifting towards the right on the graph. The M/A ratio increases with particle size, and it can thus be expected that the recovery to the tailings will decrease accordingly. Similar to the case of a decrease in density, the gravitational force on the particles will decrease with decreasing particle size, and the particles could thus be supported by the liquid lamella.

In the case of smaller particle sizes, the recovery of particles to the tailings is less sensitive to a change in particle density. The 3.05mm cubes display a distinct recovery curve for each density fraction, while the recovery curves for the 2.10mm cubes virtually coincide. This trend can again be explained in view of the M/A ratio difference between the particles of each density fraction and particle size. The M/A ratio of a particle in each density fraction is presented in Table 1. The ratio difference between individual 2.1mm particles of the various density fractions is only 0.07 while the ratio difference for the 3.05mm particles is 0.1. The much larger ratio difference for the 3.05mm particles would result in the distinct recovery curves as shown in Figure 4.

To demonstrate the influence of particle shape on the recovery of particles to the tailings, experiments were conducted with various particle shapes at the same aeration rate used in the previous experiments. The associated recovery curves are presented in Figure 5. Three shapes were investigated, i.e. 2.1mm cubes, 2.08 x 3.38mm cylinders and 2.08 x 1.98mm discs. The expected trends as obtained with the results of the experiments described above, are followed for each individual particle shape in that the recovery to the tailings decreases with an increase in the M/A ratio. However, when the M/A ratios for the various shapes are compared, it is found that these trends are not continued. For example, although the M/A ratio of the 3.5 SG cubes is higher than that of the 2.9 SG cylinders (1.23 and 1.15 respectively), the cubes are more easily recovered to the tailings. This clearly shows that the bubble films have less "grip" on the rounded area of the cylinder, while the shape of the cube lends itself more to support by the bubble films.

This observation is substantiated by comparison of the results for the 3.5 SG disk and the 2.7 SG cylinder (M/A ratios of 1.19 and 1.07 respectively). Although it is expected that the recovery of the disc-shaped particles to the tailings would be less than that of the cylinders because of their larger M/A ratios, the opposite is true. This can be attributed to the fact that the cylindrical area of the disc constitutes 65 percent of its total surface area, while the corresponding figure for the cylinder is 76 percent. Based on these observations, it can be expected that when treating particles of the same M/A ratio in the froth, flat particles would be recovered to the tailings in preference to cubic, disc-shaped, cylindrical and spherical particles, in that order.

Figure 5. The Effect of Particle Shape on the Recovery of Particles to the Tailings.

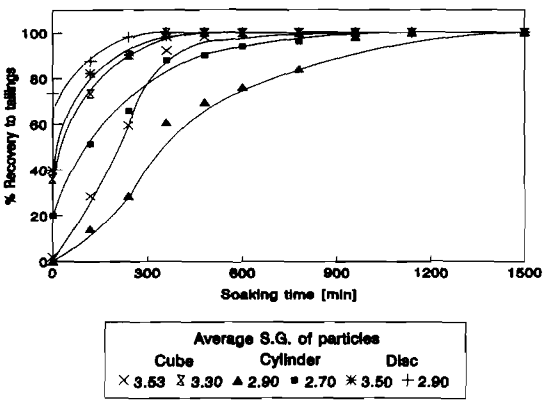
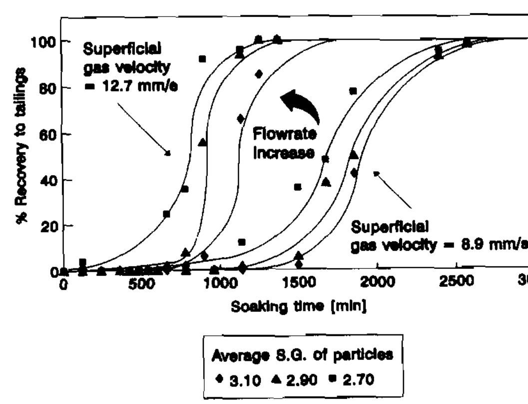


Figure 6. The Effect of Aeration Rate on the Recovery of Cubic Particles to the Tailings.



By varying the aeration rate of the cell, various froth characteristics such as the rigidity and thickness of bubble films and the residence time of the bubbles in the cell can be modified. The effect of aeration rate on the recovery of 3mm cubes to the tailings was investigated. Tracers with specific gravities of 3.10, 2.90 and 2.70 were used in conjunction with two aeration rate settings: (1) superficial gas velocity of 12.7 mm/sec for compartments #1A and #1B and (2) superficial gas velocity of 8.9 mm/sec for compartments #1A and #1B.

As can be seen in Figure 6, an increased aeration rate results in an increased recovery of hydrophobic particles to the tailings. It can be expected that the aeration rate will have some influence on the recovery of even highly hydrophobic particles, seen in the light of the previous work on bubble film thinning and rupture (Dippenaar, 1982) (Hemmings, 1981). The characteristics of the froth such as the rigidity and the thickness of the bubble films, as well as the size and the residence time of the bubbles, are closely related to the aeration rate. An increased aeration rate would firstly increase the thickness of the bubble films in the froth since there is less time for bubble film drainage, and secondly would decrease the residence time of the bubbles. The increased bubble film thickness would increase the time taken for bubble film thinning and this would result in an increased recovery to the tailings. In addition, the recovery to the tailings would increase if the particles do not have sufficient time to settle through the froth before they reach the splitter plate. It can therefore be expected that the aeration rate would be a very important control parameter in the reverse froth flotation technique.

There does not appear to be any relationship between the aeration rate and the hydrophobicity of particles in terms of their recovery to the tailings. As can be seen from Figure 6, the results follow the same trends for the particles of various densities. Although the curves move to the left with an increased aeration rate, they do so in a uniform manner, i.e. their S-shape remains.

CONCLUSIONS

A novel separation technique that could treat coarse hydrophobic particles at a low power input and without the addition of alternate flotation reagents, has been developed. The concept is based on the fact that a coarse particle with a highly hydrophobic surface will repel the bubble films in a froth and thus drop through the froth under the influence of gravity. The gangue or hydrophilic particles, in turn, are supported by the bubble films in the froth and are therefore recovered as the floating product.

The results of the work have shown that prolonged soaking times of the coated tracers in the water-frother mixture result in an increase in particles reporting to the tailings due to a decrease in particle wettability. The recovery of particles to the first concentrate increased as the particle density and size increased. It was also found that the effect of density on the particle behaviour increased as the particle size increased due to the greater difference between the mass to area ratios (M/A) of the particles in each density fraction. The shape of the particles also influenced their recovery significantly - it was noted that in addition to the M/A ratio of the particle, its sphericity contributed to its behaviour. It can therefore be expected that when treating particles of the same M/A ratio, spherical particles would be recovered to the first concentrate in preference to (in recovery order) cylindrical, disk-shaped and cubical particles.

An increased aeration rate decreased the recovery of particles to the underflow product, presumably due to a decrease in residence time of the bubbles, and therefore the particles in the froth, and the increased bubble film thickness. It can therefore be expected that the aeration rate would be a very important control parameter in the reverse froth flotation technique.

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