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Fine pyrite flotation in an agitated column cell

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Abstract

The flotation of fine pyrite has been studied in a 0.1 m × 1.9 m agitated column. The variables studied were agitation, air and slurry feed rates. The recovery and selectivity were determined for various size fractions as a function of the column operating variables. The results obtained indicate that particles less than 25 μm may be selectively recovered provided the agitation rates are kept below 400 rpm. Increasing the airflow rate at a fixed agitation rate of 400 rpm resulted in a decrease in the selectivity. The loss of selectivity at higher agitation and airflow rates is attributed to the increased entrainment of fine gangue particles. The results obtained suggest that maximum external power input of about 0.3 kW/m^3 is required for separation of the fine pyrite. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: fine pyrite; flotation; agitation

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1. Introduction

The supply of high-grade mineral deposits continues to decline globally and it is becoming increasingly necessary to process complex low-grade ores. Typically, the mineral value in these ores is finely dispersed within the matrix. Liberation of the mineral value must be accomplished by fine grinding. It is therefore important to develop flotation and other separation processes that can operate efficiently at fine sizes. Unfortunately, there are both economic and technological challenges for efficient

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separation at fine sizes. Fine particles present a high specific surface area and are not therefore readily amenable to separation by flotation. It is for this reason that the feed to flotation circuits in most traditional mineral separations is deslimed. However, in some applications, the need to meet product specifications may necessitate processing at fine sizes. For example, at the Cleveland Cliffs, Inc., the iron ore is ground to 85% passing 25 μm to liberate the silica. The finely ground ore is beneficiated by flocculation and cationic flotation. Similarly, in the base metal industry, fine grinding is often employed to effect liberation of the mineral value. The present study evaluates the effectiveness of an agitated flotation column for fine pyrite separation.

A major development in fine particle flotation has been bubble column flotation (flotation columns and their variations, including the Jameson cell). Several studies have shown that flotation columns can be effectively deployed in fine particle flotation (e.g., see Luttrell et al., 1988; Finch and Dobby, 1990; O'Connor et al., 1993; Harris et al., 1994; Ityokumbul and Trubleja, 1998). These column devices like their counterparts in the chemical industry have found widespread application. While flotation columns were initially developed and applied at Inspiration Copper in the mid-1910s, they were plagued by poor design of the gas sparging system (Ityokumbul, 1993). The commercial success of recent flotation columns is due in part to their ability to overcome these design flaws.

In order for fine particles to be collected in a flotation system, they must collide with and adhere to the air bubbles. Unfortunately, fine particles typically lack the inertia to collide with air bubbles and instead follow the liquid streamlines. It can be shown that solid particles will follow the liquid streamlines if (Jameson et al., 1977):

$$\frac{\rho_{\mathrm{p}} d_{\mathrm{p}}^2 U_{\mathrm{b}}}{9\mu d_{\mathrm{b}}} \ll 1. \tag{1}$$

For bubble sizes in the range 1.5 to 2 mm, the ratio of bubble rise velocity to size for frothers commonly used in flotation is approximately 100 s^{-1} (Ityokumbul et al., 1995). Assuming a slurry viscosity and particle density of 1.5 mPa s and 3300 $\mathrm{kg/m}^3$, respectively, the inequality in Eq. (1) reduces to:

$$d_{\mathrm{p}} \ll 200\ \mu\mathrm{m}. \tag{2}$$

For an order-of-magnitude estimate, Eq. (2) suggests that particles less than about 20 μm will follow the liquid streamlines. Thus, for separation by flotation to be effective, the fine particle–bubble collision process must be promoted. This process is considered to be analogous to shear-induced flocculation. Thus, in the present work, static mixers have been employed to enhance the collision of fine pyrite particles with air bubbles in a column cell.

2. Experimental methods

Pilot plant studies were carried out in a 0.1-m-diameter stirred flotation column. The height of the column (measured from the air sparger to the cell lip) was 1.9 m, with the

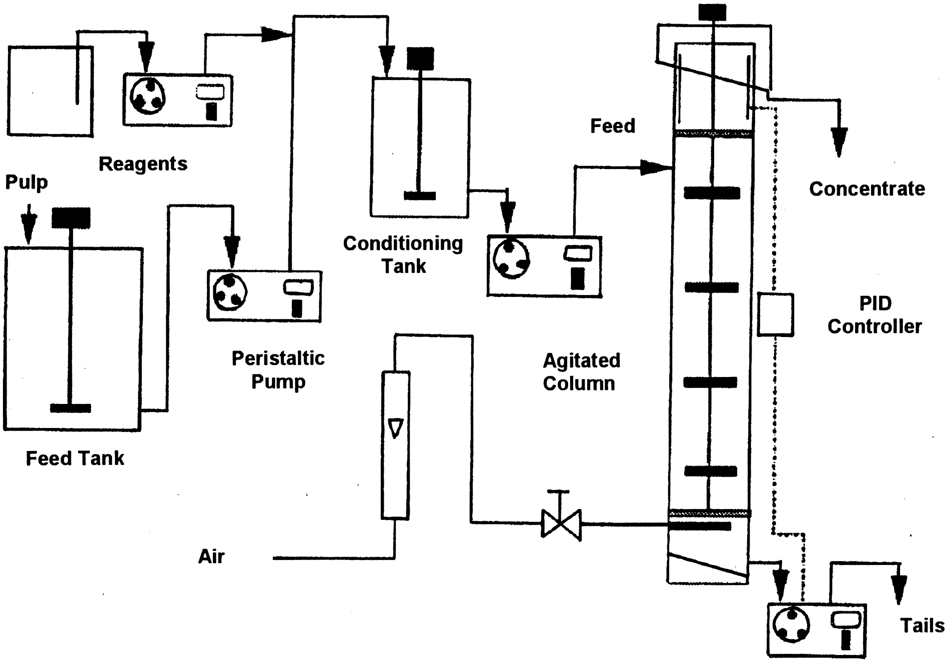

Fig. 1. Agitated column cell pilot plant used in flotation tests.

feed introduced 0.25 m from the cell lip. Gold-bearing pyrite ore was conditioned in an agitated tank and introduced into the column using a variable speed peristaltic pump. Frother (Dowfroth 200) and collector (sodium mercaptobenzothiazole) were added to the conditioning tank at 90 and 100 g/ton, while the solid feed concentration and conditioning time were fixed at about 17 wt.% and 6 min, respectively. The pulp level was monitored and controlled by measuring the pulp conductivity and PID control of the tailings pump speed, respectively. Fig. 1 shows the schematic of the experimental setup.

The feed material contained 1.8% pyrite with approximately 62% of the pyrite present in the minus 25 μm size fraction (see Table 1). All the flotation experiments were carried out at pH 4.0–4.2 while the froth height was fixed at 5 cm. While

Table 1
Grade and distribution of pyrite with size in the feed

Size fraction (μm)	Wt.%	Pyrite grade (wt.%)	Cumulative distribution (wt.%)	
			Mass	Pyrite
+106	2.5	0.174	2.5	0.2
−106+75	22.7	1.218	25.2	15.5
−75+38	6.8	2.152	32.0	24.6
−38+25	6.5	2.507	38.5	33.6
−25	61.5	1.983	100	100

traditional column flotation test work is carried out with wash water addition, this was not the case in the present study. The variables investigated were:

- Agitation rate (0 to 900 rpm),
- Superficial air velocity (1 to 1.99 cm/s),
- Superficial pulp velocity (0.52 to 1.06 cm/s).

For each experiment, the froth product and tailings were collected and analyzed for solids concentration, size distribution, and pyrite content. Because the quantity of material in some of the size fractions was small, the size fractions were subsequently reported as coarse (+75 μm), intermediate (−75 + 25 μm) and fine (−25 μm).

3. Results and discussion

3.1. Effect of agitation

The effect of agitation rate on flotation response is shown in Table 2. In general, pyrite and water recovery increased with agitation rate. While pyrite recovery above 400 rpm increased marginally, the water recovery increased sharply under the same conditions. Since the recovery of fine gangue increases with water recovery, lower product grades were expected for agitation rates exceeding 400 rpm. Indeed for agitation rates in the range 0–400 rpm, the concentrate grade remained fairly constant. However, above 400 rpm, the concentrate grade decreased sharply with increasing agitation rate. This is suggestive of increased entrainment of gangue particles at these higher agitation rates. It is evident from the foregoing that moderate agitation rates (< 400 rpm) are beneficial in fine particle flotation. The improvement in fine particle recovery is attributed to improved contact between the fine particles and the air bubbles.

In order to confirm these trends, a detailed analysis of the concentrate was carried out and the results are presented in Fig. 2. For all size fractions, the product grade declined for agitation rates above 400 rpm. However, the drop in the product grade increased with decreasing size. It is noted that the froth solids concentration also appears to exhibit a transition at 400 rpm. For example, froth solids concentration was higher, equal and lower than the feed concentration at agitation rates below, equal and above 400 rpm, respectively. In the light of the foregoing, it is concluded that the optimum agitation rate

Table 2
Variation of flotation results with agitation rate in the stirred column

Agitation rate, RPM	Flotation concentrate			
	Pyrite recovery (%)	Pyrite grade (wt.%)	Water recovery (kg/h)	Wt.% solids
0	69	88	1.03	29.9
300	78	88	1.37	28.7
400	80	81	2.88	16.9
500	86	31	18.9	9.2
600	86	29	18.4	10.7
900	87	11	43.9	10.7

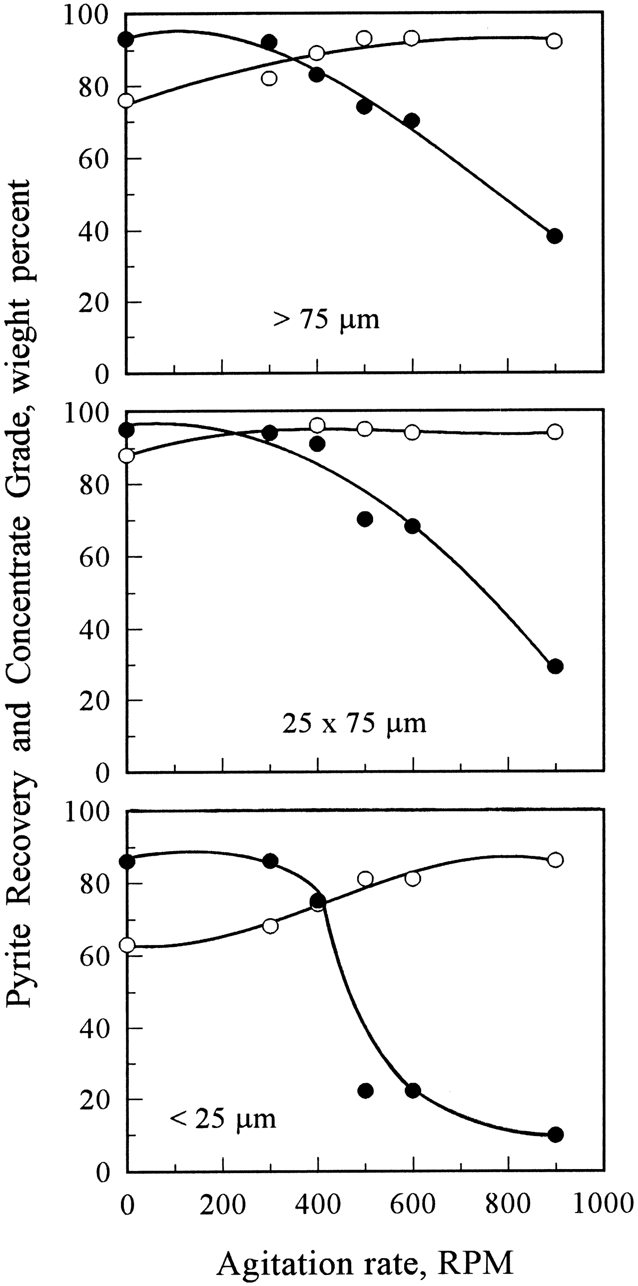

Fig. 2. Variation of pyrite recovery and grade with agitation rate of stirred flotation column cell. Open and filled symbols are for recovery and grade, respectively.

for fine pyrite recovery in the present study is 400 rpm. Consequently, all subsequent tests were carried out at 400 rpm.

The power consumption in the agitated column was determined and the results are shown in Table 3. The results show that best flotation was observed when the energy dissipation rates were of the order of 0.3 $\mathrm{kW/m^3}$ or about one order of magnitude lower than those encountered in conventional flotation cells. This finding explains why conventional flotation cells are not effective in fine particle flotation. It is noted that in a conventional flotation cell, the mechanical energy input affects bubble generation, suspension of solid particles, and also promotion of contact between the air bubbles and the suspended solid particles in the pulp. By contrast, in a column cell, these processes can be separated and optimized independently. For example, the settling action of the solid particles ensures their suspension in the slurry. Similarly, bubble generation can be independently controlled. Thus, agitation in a stirred column cell may be optimized to promote fine particle–bubble collision in the pulp. The collision process will be controlled by shear-induced velocity gradients in the pulp. By definition:

$$G = \sqrt{\frac{(P/V)}{\mu}}\,, \tag{3}$$

where G is the velocity gradient, P/V is the energy dissipation rate per unit volume of slurry and μ is the liquid viscosity. The velocity gradient at 400 rpm was computed to be about 540 $\mathrm{s^{-1}}$. In the light of the foregoing, it is suggested that the velocity gradients be limited to about 500 $\mathrm{s^{-1}}$ or less in fine particle flotation.

The size-specific recovery and grade data clearly show that agitated and unagitated column cells are effective in fine particle flotation. In traditional column flotation, wash water is employed to suppress the entrainment of fine gangue particles. The use of wash water allows the columns to be operated under positive bias where the tailing flow rate is higher than that of the feed. While wash water was not employed in our study, it is noted that the product recoveries and grades were quite high. For example, at the optimum agitation rate of 400 rpm, the pyrite recoveries in the fine, intermediate and coarse fractions were 74%, 96% and 89%, while the corresponding pyrite grades were 75%, 91% and 83%, respectively. The results obtained in our study are consistent with those of Harris et al. (1994) who carried out an evaluation of different flotation technologies for fine coal cleaning. Harris et al. (1994) reported that column flotation was the most effective technology for selective cleaning of fine South African coals.

Table 3
Power input as a function of agitation and aeration rates

Agitation rate, RPM	Power input at different air velocities ($\mathrm{kW/m^3}$)	
	$U_g = 0$ cm/s	$U_g = 0.54$ cm/s
300	0.15	0.13
400	0.33	0.31
500	0.63	0.60
600	1.05	1.00
900	3.30	3.00

3.2. Effect of slurry feed rate

The variation of concentrate flow rate and grade with slurry feed rate was studied at a fixed gas velocity of 1.49 cm/s at two agitation rates (0 and 400 rpm) and the results are shown in Fig. 3. For all the conditions reported here, the concentrate flow rate increased with slurry feed rate and was higher in the agitated system. In general, higher concentrate grades were observed in the unagitated system, however, the difference became less pronounced at the highest slurry feed rate. The results suggest that the tests were carried out under free flotation conditions and the separation was highly efficient even though a shallow froth depth and no wash water was employed to suppress fine gangue recovery.

From the concentrate flow rate and grade, the pyrite recoveries were computed. On average, agitation at 400 rpm produced a 13% increase in pyrite recovery. For a valuable

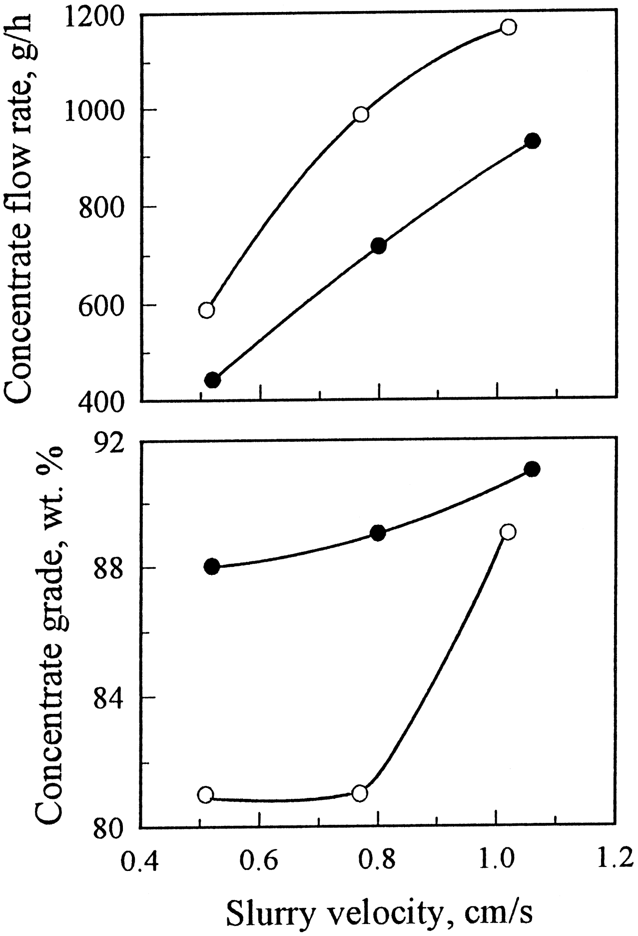

Fig. 3. Effect of slurry velocity of fine pyrite flotation. Open and filled symbols for agitated and unagitated column systems, respectively.

product, the increase in recovery at comparable product grades may justify the increased cost associated with agitation of the column cell.

3.3. Effect of gas velocity

The effect of gas velocity on fine pyrite flotation was studied at a slurry velocity of 0.51 cm/s and agitation rate of 400 rpm. The variation of pyrite recovery and grade with gas velocity is shown in Fig. 4. As expected, the pyrite recovery increased with superficial gas velocity, with the effect being more pronounced for the finest fraction. However, the pyrite grade for the finest fraction decreased sharply with increasing gas velocity. It is apparent from the foregoing that fine gangue entrainment increased with gas velocity. Overall, the pyrite recovery increased from 71% to 86% while the product grade decreased from 92% to 26% as the gas velocity was increased from 1 to 2 cm/s, respectively. The drop in product grade was directly related to the water recovery. The results suggest that agitation strongly influences the hydrodynamics in the flotation cell and the effect increases with aeration. The results of this study agree with those reported earlier by O'Connor et al. (1993) who also found that the concentrate grade decreased with increasing superficial gas velocity.

As indicated earlier, the specific power consumption at the optimum agitation rate was estimated to be of the order of 0.3 kW/m^3. For unagitated column cells, Ityokumbul et al. (1999) have shown that the velocity gradient may be estimated using the relationship (Ityokumbul et al., 1999):

$$G = \sqrt{\frac{U_g\, g\, \rho}{\mu}}\,. \tag{4}$$

Using the optimum velocity gradient determined for the agitated column cell (550 s^{-1}), the maximum gas velocity for fine particle flotation in an unagitated column cell is estimated to be 3 cm/s. It is noted that O'Connor et al. (1993) reported poor pyrite recoveries in their unagitated flotation column at gas velocities in the range 2.7–5 cm/s. This gas velocity range corresponds to the transition from bubbly to churn turbulent flow regime (Ityokumbul, 1993).

In column flotation, a major expense is related to air consumption. Szatkowski and Freyberger (1985) introduced the concept of an air consumption factor, a pseudo-efficiency term relating the amount of air needed to generate 1 kg of the product. Fig. 5 shows the variation of the air consumption factor with superficial gas velocity. Also plotted for comparison are the data of O'Connor et al. (1993) for fine pyrite flotation in an unagitated column cell. Within the limits of experimental error, the results are in good agreement. Our findings clearly illustrate the limitation of fine particle flotation — the huge quantities of air required for separation. In the present study, the lowest value encountered was of the order of 300 l/kg of product. Szatkowski and Freyberger (1985) suggested that the theoretical limit for flotation may be determined using the relationship:

$$\lambda = \frac{\rho_s - \rho_l}{\rho_s\, \rho_l}, \tag{5}$$

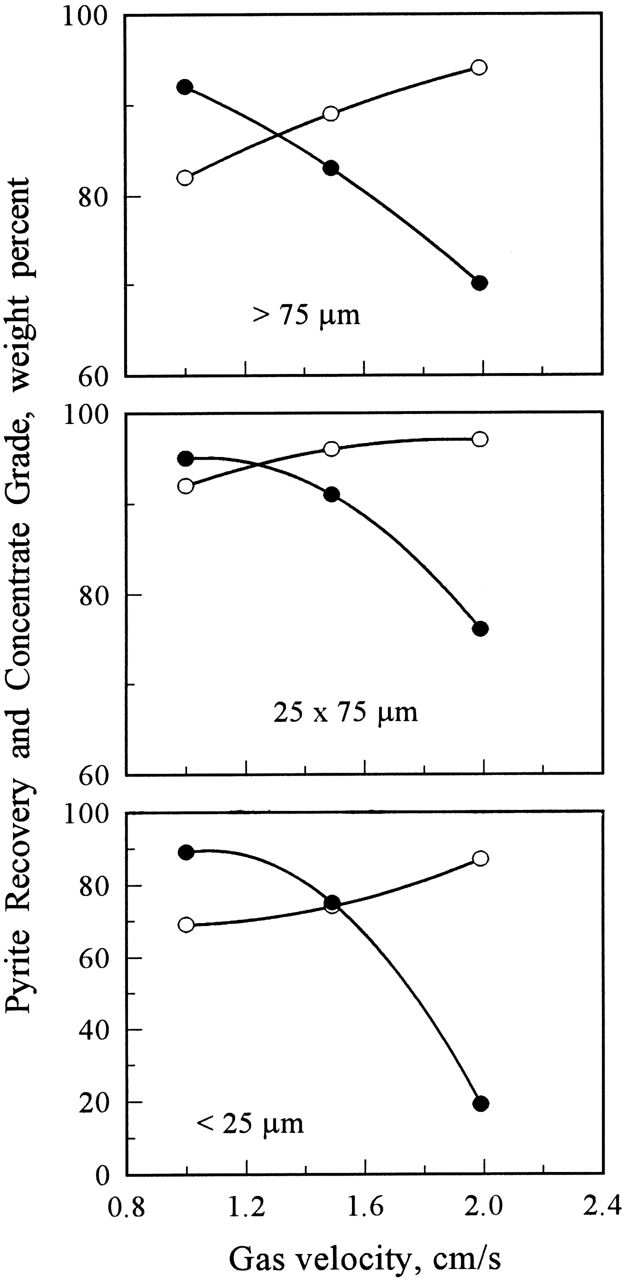

Fig. 4. Variation of pyrite recovery and grade with gas velocity in the stirred flotation column cell. Open and filled symbols are for recovery and grade, respectively.

where λ is the theoretical air requirement. For pyrite flotation, Eq. (5) predicts a value of 0.8 l/kg of product. The values determined in the present study are much higher than

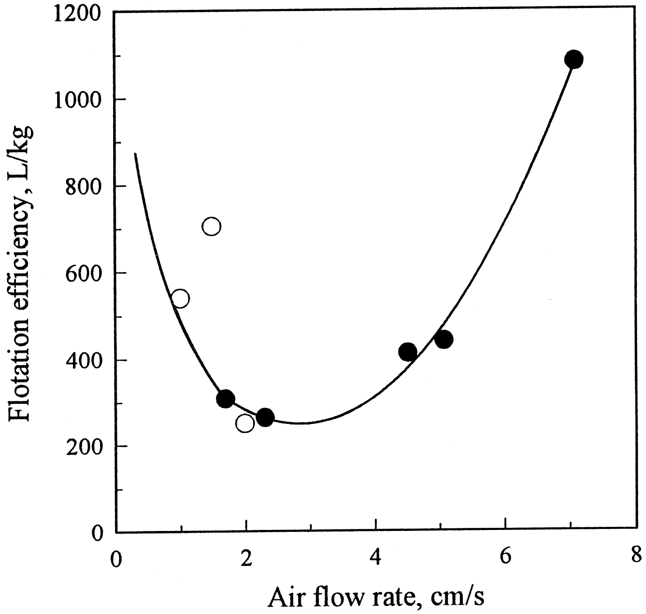

Fig. 5. Comparison of flotation efficiency from agitated (open symbol) and unagitated column cells (filled symbol). Data for the unagitated column taken from O'Connor et al. (1993).

the theoretical values estimated using the relationship of Szatkowski and Freyberger (1985). The reasons for this discrepancy are not entirely clear at the present time, but may be related to bubble size effects. For example, the average bubble size in the study of Szatkowski and Freyberger (1985) was in the range 10–100 μm, while in our study, the bubble sizes were one to two orders of magnitude larger. Since flotation is an interfacial phenomenon, the surface area available for particle collection decreases with increasing bubble size. Thus, given the larger bubble size in our study, the higher air consumption observed in the present study was expected. It is also noted that in talc flotation (Kho and Sohn, 1989), the air consumption was about 20 l/kg, a value that is one order of magnitude higher than that predicted by Eq. (5).

It is evident from the foregoing that the limit of fine particle flotation will be an economic one. If fine grinding is needed for liberation, column flotation (agitated and unagitated) may be the only viable process options. The additional expense associated with the operation of the agitated column cell may be justified by the increased recovery of the product.

The direct power requirements in the operation of agitated and unagitated column cells are modest. However, the capital expenditure and power requirement for the air compressor farmhouse may be considerable. This means that in comparing column cells with other flotation technologies, these costs must be included in the cost model. For example, the power draw at the optimum agitation rate was determined to be of the order of 0.3 kW/m^3. While this value is considerably smaller than that typically encountered in conventional flotation (1.3 to 4 kW/m^3), the air requirements for the separation were of the order of 200–300 l/kg of product. In the light of the foregoing, it is suggested that air consumption may represent a useful parameter for direct comparison of different flotation technologies.

3.4. Froth characteristics and product grade

The column operational parameters employed in the present study (froth depth, wash water use) were different from those employed in conventional flotation. For example, the froth depth in our study was only 5 cm and wash water was not used to suppress fine gangue recovery. The rule-of-thumb in column flotation is that deep froths and wash water are necessary to effect fine gangue rejection. However, the results of the present study show that high product recoveries and grades are possible without deep froths and application of wash water.

In order to investigate if there is a relationship between froth characteristics and grade, the concentrate grade is plotted as a function of froth solids concentration and the results are shown in Fig. 6. The results show two distinct clusters characterized by high and low product grades. In general, high product grades were observed when the froth solids concentration was above about 17 wt.%, which in the present study was the feed solids concentration. Conversely, low product grades were observed when the froth solids concentration was below 17 wt.%. This observation suggests that wash water may not be necessary in suppressing fine gangue recovery, provided the froth drainage produces a 17 wt.% or higher concentrate. If this trend is confirmed in other column studies, the froth solids concentration may emerge as an important control variable in fine particle flotation.

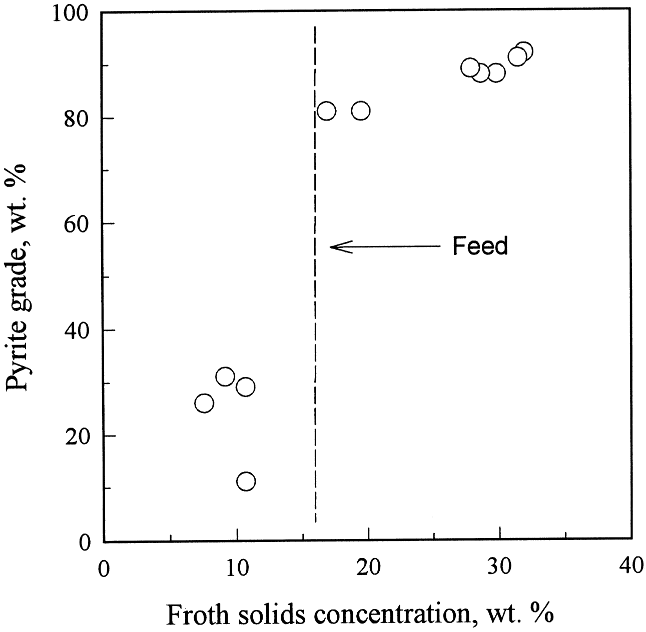

Fig. 6. Variation of pyrite grade with froth solids concentration.

4. Conclusion

Fine pyrite flotation has been carried out in an agitated column cell. The optimum agitation rate for the separation was determined to be 400 rpm, with the product grade dropping sharply at higher agitation rates. At the optimum agitation rate, the average velocity gradient was estimated from the measured specific energy dissipation rate to be about 540 s^{-1}. Agitation of the column cell appears to promote particle–bubble contact, producing an average increase in pyrite recovery of 13% at comparable product grades. While wash water was not employed, high concentrate grades were obtained with proper control of agitation and airflow rates. Air consumption for the fine pyrite separation was determined to be of the order of 200–300 l/kg and was comparable to that estimated in unagitated column cells.

5. Nomenclature

d_b	Bubble diameter
d_p	Particle diameter
U_b	Bubble rise velocity
ρ_l	Liquid density
ρ_p	Particle density
λ	Theoretical air requirement for separation by flotation
μ	Liquid viscosity

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