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A Study on Picobubble Enhanced Coarse Phosphate Froth Flotation

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Abstract: Effects of picobubbles on froth flotation of coarse phosphate particles ($-1180\ \mu m + 425\ \mu m$) have been investigated with a specially designed flotation column. Cavitation generated picobubbles are characterized by inherently high probability of collision, high probability of attachment, and low probability of detachment during froth flotation due to their tiny size and high surface activity. Test results obtained with a 5 cm in diameter laboratory scale flotation column indicate that picobubbles are effective in enhancing the flotation of coarse phosphate particles, and increasing the flotation recovery by 10 to 23 absolute percentage points under various conditions. The required collector dosage and frother dosage for a given flotation performance were reduced by one-half to two-thirds.

Keywords: Coarse phosphate particle, picobubble, flotation recovery, particle bubble interaction

INTRODUCTION

The Florida phosphate industry accounts for up to 85% USA phosphate production (1), wihch is the largest phosphate rock producer in the world. The phosphate ore that occurs as shallow deposits of gravel, sand, and clay is usually washed and classified into three major size fractions as shown in Fig. 1. The coarse $+1180\ \mu m$ portion is primarily phosphate pebble and does not require upgrading. The fine ($-106\ \mu m$) portion that contains

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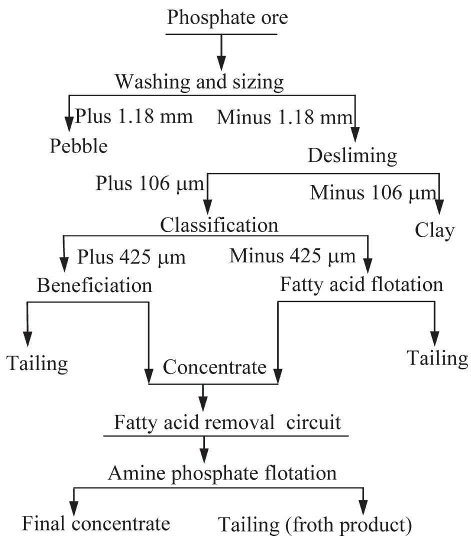

Figure 1. A generalized Florida phosphate flowsheet.

virtually all of the clay minerals is discarded in the hydrocyclone overflow (2). The remaining −1180 μm + 106 μm fraction is classified into coarse (e.g. −1180 μm + 425 μm) and fine (e.g. −425 μm +106 μm) fractions, which are upgraded using conventional flotation. Generally, conventional flotation cells can be used to produce acceptable concentrate grades from the fine flotation feed (−425 μm +106 μm) with recoveries in excess of 90%. However, recoveries higher than 90% are very difficult to achieve with the coarser (−1180 μm + 425 μm) flotation feed.

A number of studies have been conducted on coarse phosphate flotation. Soto and Barbery (3) showed that a negative bias flotation column improved the coarse particle recovery. Moudgil (4) reported that the recovery of coarse particles can be enhanced by means of collector emulsification. Maksimov (5) reported that weak agitation combined with sufficiently high ascending pulp flow in a mechanic flotation cell substantially increased the flotation recovery of coarse mineral particles. The benefits of negative bias were also recognized by (1). However, the improvement in the flotation recovery of coarse phosphate flotation is still limited and much better flotation performances are expected by the industry. The present study was conducted to investigate the effectiveness of picobubbles in improving coarse phosphate particles.

EXPERIMENTAL

A picobubble enhanced coarse phosphate froth flotation column of 5 cm in diameter was specially designed, which is schematically illustrated in

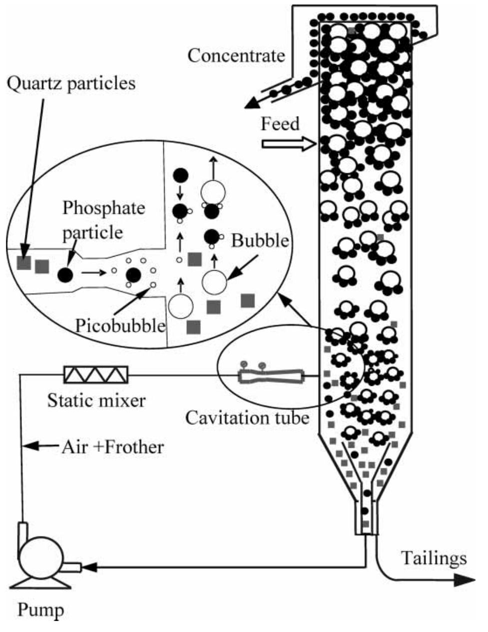

Figure 2. Schematic illustration of specially designed column.

Fig. 2. The column was integrated with a hydrodynamic cavitation tube to produce picobubbles. The picobubbles generated by the cavitation tube are generally smaller than 1 μm (6), which are inherently efficient in creating bubble-particle collision and adhesion. The conventional sized bubbles are generated using a static mixer. Our recent measurements of picobubble size indicated that the picobubbles were about two orders of magnitude smaller than microbubbles produced by the static mixer and the data will be reported in another publication. The cavitation tube and the static mixer were configured in such a way that the circulating slurry went through both of them in series when picobubbles were needed and the venturi tube was bypassed when no picobubbles were required.

As shown in Fig. 2, the conditioned phosphate feed slurry entered the column tangentially in the upper pulp zone. Particles collected by rising bubbles ascended to the top of the column. Those that settled to the bottom of the column were pumped through the cavitation tube and the static mixer to have more chances for recovery. The slurry jet out of the neck of the venturi cavitation tube at a speed of 6 to 10 m/s caused cavitation in the stream with gas nucleation taking place on the particle surface and in water.

The coarse phosphate sample ($-1180+425$ μm) was acquired from a Florida phosphate company. Fatty acid (FA-18G) and fuel oil were mixed thoroughly at 1:1 ratio by weight as the flotation collector. A glycol frother (F-507) was used for the coarse phosphate flotation tests. Sodium hydroxide was used to adjust the pH value of flotation feed slurry between 9.1 and 9.5. The flotation feed was conditioned for three minutes at a predetermined 75% solids concentration using a mechanical agitator. The conditioned phosphate sample was diluted to 25% solids content by weight and fed tangentially into the flotation column through a peristaltic pump.

RESULTS AND DISCUSSION

In order to evaluate the effects of picobubbles on coarse phosphate flotation performance, a number of experiments were carried out at varying collector dosage, frother dosage, phosphate particle size, and solids feed rate. Two coarse phosphate samples (A, B) used in this study originated from two different phosphate deposits in Florida. The phosphate sample B (mainly composed of black phosphate particles) is more difficult to float than the phosphate sample A (mainly composed of brown phosphate particles). The test results were presented in the following sections.

Collector Dosage

Figure 3 shows the effect of picobubbles on flotation recovery of the phosphate sample A at varying collector dosages from 0.3 to 2.7 kg/ton. In these experiments, the solids feed rate, superficial air velocity, and frother

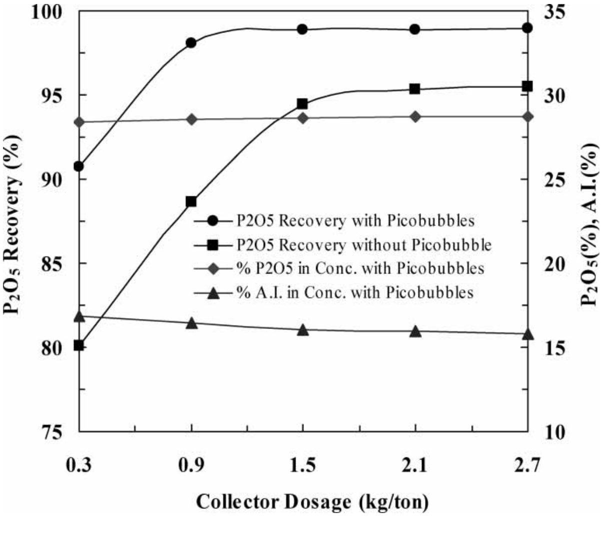

Figure 3. Effects of picobubbles on flotation recovery at varying collector dosages. P_2O_5 grade in concentrate was 28–29%.

dosage were kept constant at 240 g/min, 1.0 cm/s, and 10 ppm, respectively. In the absence of picobubbles the flotation recovery increased significantly as the collector dosage increased from 0.3 to 1.5 kg/ton, after which the flotation recovery remained essentially constant at 95%. In the presence of picobubbles, the maximum flotation recovery of more than 98% was achieved at a lower collector dosage of 0.9 kg/ton, producing a concentrate of 28–29% P_2O_5. In the absence of picobubbles the maximum flotation recovery was only 95%, which was achieved at a collector dosage of 2.1 kg/ton. Figure 3 indicates that picobubbles increased flotation recovery by up to 12% when collector dosage was less than 0.9 kg/ton. The product P_2O_5 grade increased and A.I. content in the concentrate decreased slightly as the collector dosage increased from a dosage of 0.3 kg/ton to 0.9 kg/ton. This is because the coarse high grade phosphate particles are more difficult to be floated than the fine phosphate particles, especially at lower collector dosages. When the collector dosage increased, higher grade coarse phosphate particles floated more easily, resulting in higher product grade and lower A.I. content in the concentrate.

Figure 3 also indicates that at a given P_2O_5 recovery, the presence of picobubbles decreased the required collector dosage because picobubbles were produced from air naturally dissolved in water and they acted as the secondary collector on particle surface. At a certain collector dosage, the presence of picobubbles increased P_2O_5 recovery since picobubbles generated on a particle surface by cavitation naturally attach to the particle, eliminating the collision and attachment process which is often the rate determining step for flotation. Picobubbles can reduce the detachment probability during the rise of particle-bubble aggregate in the pulp zone of the column and thus improve the flotation efficiency of coarse particles. Because the attachment between picobubbles and conventional-sized bubbles is more favored than bubble-solid attachment, picobubbles on particle surface may activate flotation by promoting the attachment of particle and conventional-sized bubbles, as illustrated in Figure 4.

Frother Dosage

The effect of picobubbles on P_2O_5 recovery of the phosphate sample A at varying frother dosage from 0 to 20 ppm is shown in Fig. 5. The solids feed rate, superficial air velocity, and collector dosage were maintained constant at 240 g/min, 1.0 cm/s, and 0.9 kg/ton, respectively. The P_2O_5 recovery increased significantly as the frother dosage increased from 0 to 5 ppm and then levelled out as the dosage increased further; after 15 ppm, the flotation recovery remained essentially constant. The P_2O_5 recovery of more than 98% was achieved at a frother dosage of 10 ppm with a concentrate P_2O_5 content of 28–29% in the presence of picobubbles. In the absence of picobubbles, the flotation recovery was only 88.7% at a frother dosage of 10 ppm and

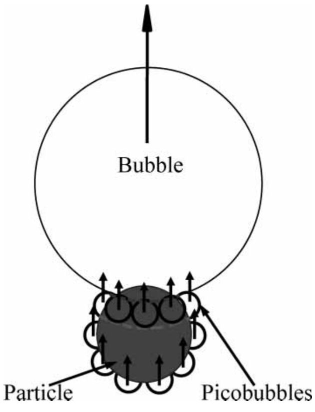

Figure 4. Enhanced bubble particle attachment by use of picobubbles.

collector dosage of 0.9 kg/ton. At a given flotation recovery, the presence of picobubbles reduced the frother dosage by more than half because picobubbles are smaller than 1 μm when they were formed from air precipitation. More frother was needed to stabilize conventional bubbles and minimize coalescence because the conventional flotation bubbles were as large as 1 mm or so when they were formed by breaking up induced air. As frother dosage increased, more coarse phosphates were floated and thus the product P_2O_5 grade increased and A.I. content decreased slightly.

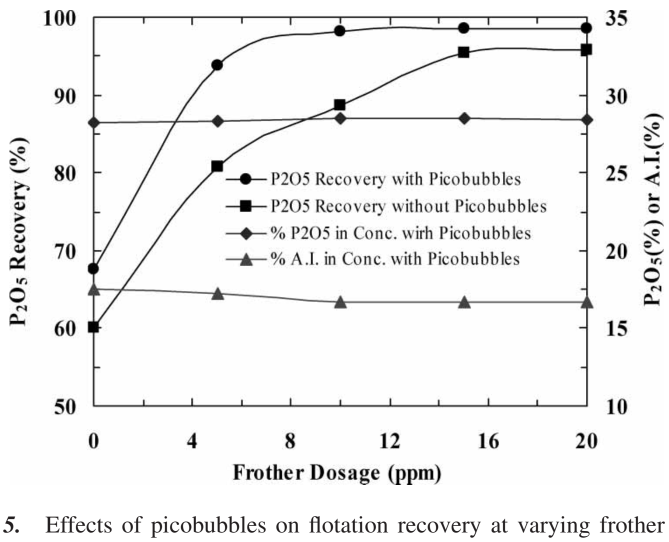

Figure 5. Effects of picobubbles on flotation recovery at varying frother dosages. P_2O_5 grade in concentrate was 28–29%.

Particle Size

Figure 6 shows the effect of picobubbles on the flotation recovery of phosphate particles of different sizes with the phosphate sample B. The data indicates that picobubbles improved the flotation recovery of all phospahte particles. The flotation recovery increased from 3% up to ~16% as the particels size increased from 0.075 mm to 1.18 mm, which indicates that picobubbles have more significant effects on coarser phosphate particles than on finer paricles.

The above results shown in Figs. 3, 5, and 6 clearly show that the use of picobubbles significantly increased coarse phosphate flotation recovery, especially at lower collector and frother dosages. At a given flotation recovery, the picobubbles co-existing with conventional-sized bubbles decreased the collector dosage and frother dosage. The effect of picobubbles on flotation recovery was particularly significant for coarser phosphate particles. One of the reasons for low flotation recovery of coarse phosphate particles is the high detachment probability. Particle detachment occurs as detachment forces exceed the maximum adhesive forces. The forces acting between a bubble and an attached particle are usually classified into four categories (7–9): the capillary force F_p, excess force F_e, real weight of particle in the liquid medium F_w, and other forces such as the hydrodynamic drag force F_d. Of these four categories of forces, F_p is generally considered to be the major adhesion force; F_w and F_d are always the detachment forces. Under normal flotation conditions, $D_b < 5.5$ mm, F_e should be considered as

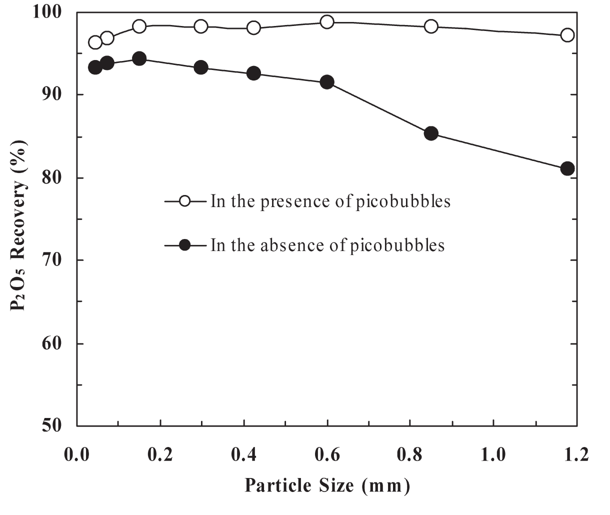

Figure 6. Effects of picobubbles on P_2O_5 recovery of different particle size.

the attachment force. The capillary force F_p and excess force F_e are typically represented by:

$$F_p = \frac{\pi D_P \gamma (1 - \cos \theta_d)}{2} \quad (1)$$

$$F_e = \frac{\pi D_P^2 (1 - \cos \theta_d)(2\gamma / D_b - \rho_w g D_b / 2)}{4} \quad (2)$$

where, γ liquid surface tension; ρ_w densities of water; θ_d critical value of three phase contact angle right before detachment.

Picobubbles on the particle surface greatly increase its hydrophobicity (θ_d) and thus considerably increase F_p and excess force F_e, favoring attachment. The research results (10) shows that hydrodynamic drag force F_d can be significantly reduced by picobubbles, which decreases the detachment force. The excess force increases with decreasing bubble size D_b, so smaller bubbles can be used to reduce coarse particle detachment and increase the upper flotation limit. Tiny picobubbles attach more readily to particles than larger bubbles due to their lower ascending velocity and rebound velocity from the surface and higher surface free energy to be satisfied.

Feed Rate

Flotation experiments with the phosphate sample B were performed at varying solids feed rates from 120 to 600 g/min with and without picobubbles. The collector dosage and frother dosage were kept constant at 0.9 kg/ton and 10 ppm, respectively in these tests. Figure 7(a) shows the P_2O_5 recovery and A.I. rejection as a function of feed rate and Fig. 7(b) the resultant separation performance curve of P_2O_5 recovery vs. A.I. rejection. Figure 7(a) indicates that the presence of picobubbles significantly increased the flotation recovery and A.I. rejection at a given feed rate. The separation performance curve shown in Fig. 7(b) clearly indicates that P_2O_5 recovery is considerably higher in the presence of picobubbles for a given A.I. rejection, implying that improved flotation selectivity or separation performance was achieved with the picobubbles. At an A.I. rejection of 89.5%, P_2O_5 recovery was about 23% higher with picobubbles than without the picobubble. It is believed that the picobubbles formed on hydrophobic particles remain attached while those on hydrophilic particles detach, which is a selective process that enhances flotation performance. The hydrophobic particles with picobubbles on the surface have a higher attachment probability and a lower detachment probability than larger bubbles produced by the static mixer in slurry, resulting in a greater flotation rate constant and flotation recovery.

The above test results are in agreement with previous work reported in literature. Shimoiizaka and Matsuoka (11) observed more efficient attachment of

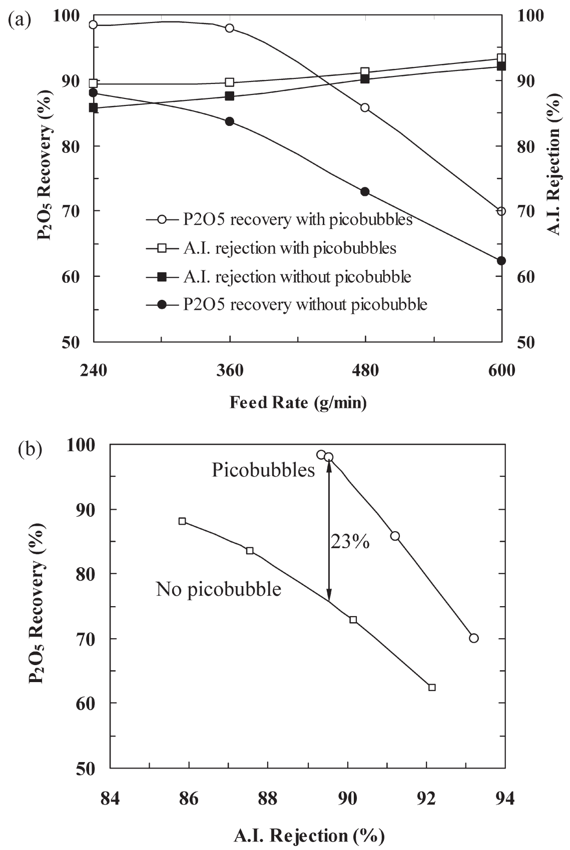

Figure 7. (a) P_2O_5 recovery and A.I. rejection vs. feed rate; (b) Relationships between the acid insoluble (A.I.) rejection and P_2O_5 recovery.

particles and improved flotation rate when tiny bubbles co-existed with conventional-sized air bubble. Klassen and Mokrousov (12) showed that the combined flotation by gas nuclei from air supersaturation and by mechanically generated bubbles produced higher flotation recovery than by either of them alone.

CONCLUSIONS

The results of phosphate particle flotation experiments, which were carried out at varying collector dosage, frother dosage, particle size, and solids feed rate, have shown that picobubbles significantly increased the flotation recovery of coarse phosphate particles. The phosphate flotation recovery was increased by up to 23 absolute percentage points by use of picobubbles. The collector dosage was reduced by one-half to two-thirds as a result of the adsorption of picobubbles on the particle surface. The frother dosage was also reduced by more than one half. Picobubbles improved flotation recovery of all particles ranging from 0.075 mm to 1.18 mm but had more significant effects on coarser phosphate than finer phosphate.

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