Separation Science and Technology
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713708471

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To cite this Article Tao, Youjun , Liu, Jiongtian , Yu, Samuel and Tao, Daniel(2006) 'Picobubble Enhanced Fine Coal Flotation', Separation Science and Technology, 41: 16, 3597 — 3607
To link to this Article: DOI: 10.1080/01496390600957249
URL: http://dx.doi.org/10.1080/01496390600957249

Separation Science and Technology, 41: 3597–3607, 2006

ISSN 0149-6395 print/1520-5754 online
DOI: 10.1080/01496390600957249

Picobubble Enhanced Fine Coal Flotation

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Abstract: Froth flotation is widely used in the coal industry to clean −28 mesh fine coal. A successful recovery of particles by flotation depends on efficient particle-bubble collision and attachment with minimal subsequent particle detachment from bubble. Flotation is effective in a narrow size range beyond which the flotation efficiency drops drastically. It is now known that the low flotation recovery of particles in the finest size fractions is mainly due to a low probability of bubble-particle collision while the main reason for poor coarse particle flotation recovery is the high probability of detachment. A fundamental analysis has shown that use of picobubbles can significantly improve the flotation recovery of particles in a wide range of size by increasing the probability of collision and attachment and reducing the probability of detachment.

A specially designed column with a picobubble generator has been developed for enhanced recovery of fine coal particles. Picobubbles were produced based on the hydrodynamic cavitation principle. They are characterized by a size distribution that is mostly below 1 μm and adhere preferentially to the hydrophobic surfaces. The presence of picobubbles increases the probability of collision and attachment and

Received 1 June 2006, Accepted 2 August 2006
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decreases the probability of detachment, thus enhancing flotation recovery. Experimental results with the Coalberg seam coal in West Virginia, U.S.A. have shown that the use of picobubbles in a 2″ column flotation increased fine coal recovery by 10–30%, depending on the feed rate, collector dosage, and other flotation conditions. Picobubbles also acted as a secondary collector and reduced the collector dosage by one third to one half.

Keywords: Collision, detachment, fine coal, froth flotation, picobubble

INTRODUCTION

Froth floatation is commonly used to clean −28 mesh (0.6 mm) or −100 mesh (0.15 mm) fine size coal. It is more efficient and cost-effective than other fine particle separation techniques such as tabling, high gradient magnetic separation, and oil agglomeration. However, it is efficient only for particles within a narrow size range, normally from 10 to 100 μm. For ultrafine and relatively coarse coal particles, the floatation performance is not quite satisfactory. It is now recognized that the low flotation efficiency of ultrafine particles is mainly due to the low probability of bubble-particle collision while the main reason for poor flotation recovery of coarse particles is the high probability of detachment of particles from the bubble surface (1, 2).

Picobubbles refer to tiny bubbles smaller than 1 μm, which can be produced using ultrasonic or hydrodynamic cavitation method (3, 4). They can be used to improve froth flotation performance by enhancing the probabilities of collision and adhesion and reducing the probability of detachment. Picobubbles preferentially nucleate at the surface of hydrophobic particles, which renders ultrafine particles adhere to picobubble without the need of collision. Picobubbles generated on particle surface also serve as a secondary collector (5), improving the probability of adhesion and reducing the need for the hydrophobizing chemical. In addition, particles are less likely to detach from smaller bubbles due to their lower acceleration force and centrifugal force associated with the detachment process, reducing the probability of detachment.

The present study was undertaken to investigate the effectiveness of picobubbles in column flotation of fine coal particles (−28 mesh). A specially designed flotation column with a picobubble generator was developed for enhancing the recovery of ultrafine coal particles that are difficult to float with conventional flotation process. Picobubbles were produced based on the hydrodynamic cavitation principle. Process parameters such as feed rate, collector dosage, and frother dosage were studied for their effects on the process efficiency.

EXPERIMENTAL

Experimental Set-up

Based on our understanding of the importance of air bubble size for flotation probability and kinetics, a picobubble enhanced flotation column, which was

2″ in diameter and 6′ in height, was specially designed which is featured with a hydrodynamic cavitation tube to produce picobubbles and a static mixer that produces the conventional sized bubbles. Details of the column are described in another publication (6). Briefly, the feed slurry enters the column in the upper pulp zone. Coal particles collected by rising bubbles ascend to the top. Those that settle to the bottom of the column are 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 causes cavitation in the stream with gas nucleation taking place on the particle surface.

Unless otherwise specified, all column flotation tests were performed under the following conditions: Superficial feed rate: 0.5 cm/s; superficial gas flow rate: 1.25 cm/s; superficial wash water rate: 0.2 cm/s; collector: 0.5 lb/t fuel oil, frother: 20 ppm MIBC. Clean coal product and tailing samples were collected after the column reached the steady state which took 10–15 minutes, depending on feed flow rate. The standard deviation of clean coal ash and yield is less than 0.3% and 1%, respectively.

Sample Acquisition and Characterization

A sub-bituminous steam coal was acquired and employed for the present study. One 55 gallon drum of the slurry sample was collected at a coal preparation plant in West Virginia, USA. Once it arrived at the lab, the slurry was thoroughly mixed and then split into 5 gallon buckets and sealed for storage and later usage. A representative sample was collected for size distribution analysis and other characterization studies. Wet screening analysis was performed using a series of U.S. standard testing. Table 1 shows the size distribution data and ash content in each size fraction. The slurry sample contained 12.6% solids and 93.51% solid particles were smaller than 300 μm.

Table 1. Particle size distribution and ash content

Size range (μm)	Weight (%)	Ash (%)	Cumulative weight (%)	Cumulative ash (%)
>600	0.38	16.81	100.00	43.43
425–600	0.78	25.02	99.61	43.53
300–425	5.33	12.03	98.83	43.68
212–300	15.86	22.39	93.51	45.48
90–212	31.85	29.06	77.65	50.20
45–90	16.37	47.88	45.80	64.90
0–45	29.43	74.37	29.43	74.37

RESULTS

To evaluate the effect of picobubbles on fine coal flotation, a number of flotation experiments were performed at varying flotation time, feed flow rate, wash water flow rate, feed solids concentration, collector dosage, and frother dosage, etc.

Figure 1 shows the separation curves (combustible recovery vs. clean coal product ash) obtained by varying flotation time from 0.5 to 4 minutes in a batch flotation test with and without picobubbles. The feed slurry volume used was approximately 3.2 liter. The separation curve in the presence of picobubbles is above that in the absence of picobubbles, indicating that picobubbles improved the flotation separation efficiency. The recovery was approximately 15% at 10% product ash in the absence of picobubbles; it increased to more than 47% when picobubles were employed.

Figure 2a shows the effects of picobubbles on combustible recovery at varying superficial wash water flow rate. The recovery was about 12–13% higher in the presence of picobubbles at all wash water rates. Figure 2b shows the separation curve of recovery vs. ash rejection. The separation curve generated with picobubbles is above the one without picobubbles, indicating picobubbles enhanced flotation separation efficiency.

Figure 3a shows the combustible recovery curves obtained with and without picobubbles as a function of superficial feed rate. Combustible recovery decreased as the feed rate increased, due to reduced flotation residence time in the flotation column. The recovery curve obtained in the presence of picobubbles is consistently above that generated without picobubbles, indicating picobubbles increased combustible recovery at a given feed rate. The increase in combustible recovery rendered by picobubbles was in the range of 15–20%. Figure 3b shows the recovery vs. ash rejection curves

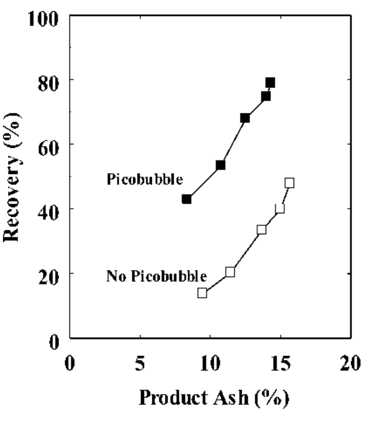

Figure 1. Effects of picobubbles on separation curve obtained by changing flotation time from 0.5 to 4 minutes in a batch flotation test.

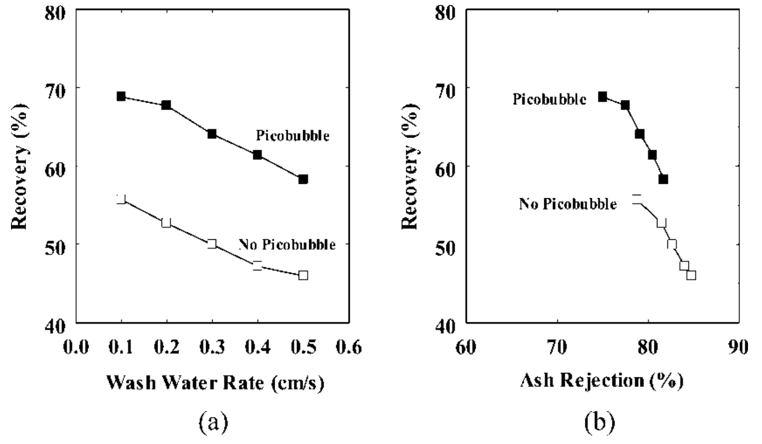

Figure 2. Effects of picobubbles on the recovery vs. wash water rate curve (a) and recovery vs. ash rejection curve (b).

produced with and without picobubbles during flotation. Obviously the separation curve in the presence of picobubbles is above the one without picobubbles. The difference in recovery is between 6–9% for a given ash rejection, indicating that use of picobubbles increased the separation efficiency by 6–9%.

Figure 4 shows the effects of picobubbles on combustible recovery (a) and product ash (b) as a function of feed solids concentration. Figure 4a indicates that the recovery decreased with increasing solids concentration, due to the fact that less bubble surface was available for each particle at higher solids concentration. However, the recovery curve with picobubbles

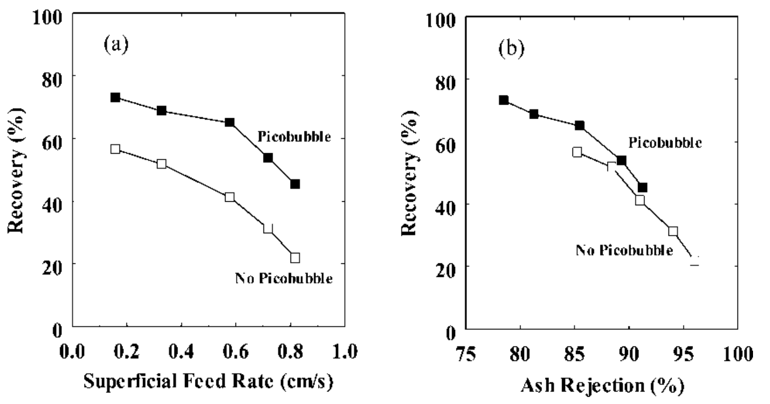

Figure 3. Effects of picobubbles on the recovery vs. superficial feed rate curve (a) and recovery vs. ash rejection curve (b).

is always substantially above that without picobubbles, suggesting that use of picobubbles significantly increased the combustible recovery. For example, the recovery was about 10% and 14% higher at 5% and 15% solids concentrations, respectively. It is also interesting to note that the product ash with picobubbles was also considerably lower than without picobubbles at solids concentrations lower than 10%, almost identical at 10–15% solids concentrations, but higher at solids concentrations of 20% or higher. The better selectivity or separation sharpness observed with picobubbles at solids percentages lower than 15% may be attributed to the preference of picobubbles to coal particles. However, it is not clear why the product ash was higher with picobubbles at solids concentrations higher than 20%. One possible reason is that at highest solids concentrations of 20% and 25% examined in this study relatively coarse coal particles captured by picobubbles, which have lower ash content than fine particles (as shown in Table 1), are less likely to be levitated from the pulp and more likely to drop from the froth due to increased resistance to travel in both pulp and froth.

Figure 5a shows combustible recovery and product ash as a function of frother dosage with and without picobubbles. Over the tested frother dosage range of 10–40 ppm, the combustible recovery was 14–20% higher in the presence of picobubbles. Although the product ash was up to 1.5% higher when picobubbles were present, the separation curve or recovery vs. product ash curve (Fig. 5b) clearly shows that picobubbles enhanced the flotation separation efficiency. Specifically, the use of picobubbles increased the combustible recovery by 13.6–17.1% at a given product ash for this coal sample.

The effects of picobubbles on flotation recovery and product ash are shown in Figure 6a as a function of collector dosage. Similar to Fig. 5a, the recovery

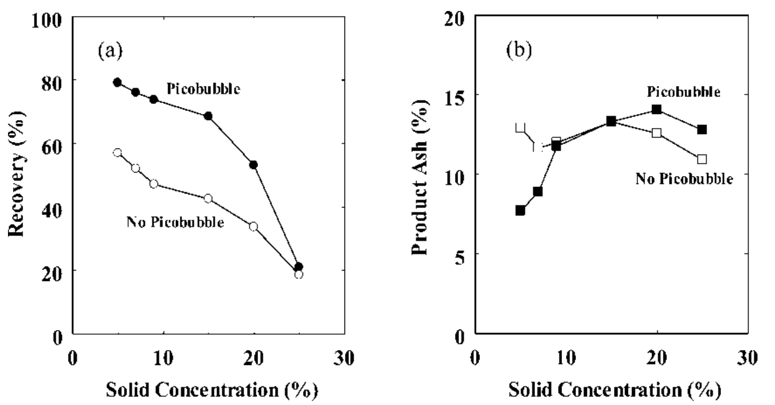

Figure 4. Effects of picobubbles on the recovery vs. feed solids concentration relationship (a) and product ash vs. feed solids concentration (b).

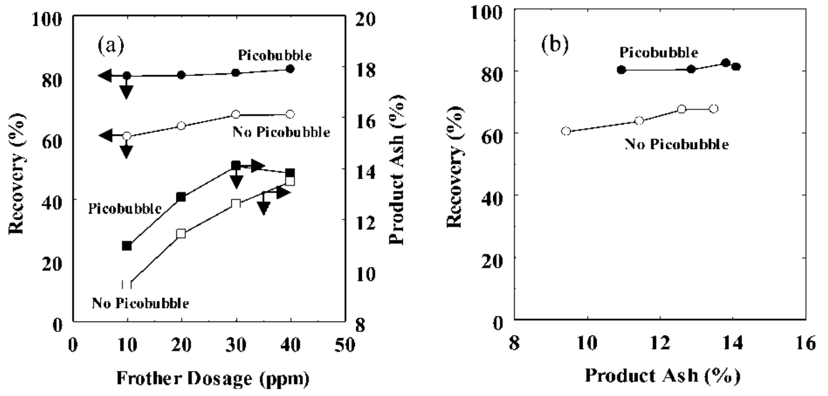

Figure 5. Effects of picobubbles on the recovery and product ash vs. frother dosage relationship (a) and recovery vs. ash rejection curve (b).

was more than 40% higher with picobubbles than without picobubbles. The product ash was less than 2% higher in most cases when picobubbles were present. Figure 6b clearly demonstrates that the separation curve obtained with picobubbles was always above the one generated without picobubbles. For example, the recovery with picobubbles was 41.4% higher than that without picobubbles for a product ash of 12%.

DISCUSSION

Froth flotation is a particle separation process that exploits the difference in surface hydrophobicity of different particles. The key to the success of this

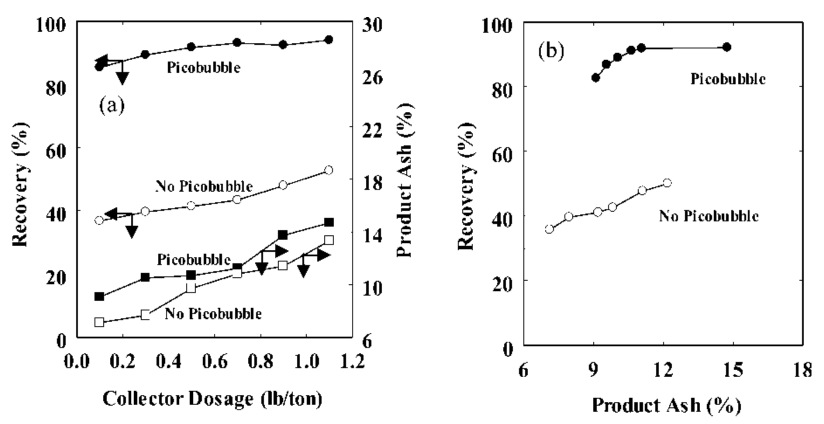

Figure 6. Effects of picobubbles on the recovery and product ash vs. collector dosage relationship (a) and recovery vs. product ash curve (b).

process is the efficient capture of hydrophobic particles by air bubbles, which is accomplished in three distinct processes: collision, adhesion, and detachment. Both bubble size and particle size have significant effects on each of the three successive steps and flotation kinetics.

In a froth flotation cell a solid particle collides with a bubble as a result of a sufficiently close encounter, which is determined by hydrodynamics of the flotation environment. The equations derived for the probability of collision (P_c) from stream functions for quiescent conditions (7, 8) or from microturbulence models for well-mixed conditions (9) indicate that P_c increases with increasing particle size and decreasing bubble size, suggesting that fine particles have a low probability of collision with bubbles and are thus difficult to be caught by bubbles, particularly by larger bubbles.

Some particles become attached to the air bubble after the collision with it and others do not. If a particle is sufficiently hydrophobic, the liquid film between the bubble and the particle thins and ruptures as a result of the attractive surface forces, eventually establishing the three phase line of contact. The attachment process is determined by hydrodynamic and surface forces between particles and bubbles. It has been found (1, 10) that the probability of adhesion (P_a) increases with decreasing bubble size D_b, meaning the smaller bubble size is favorable for increased probability of attachment.

All particles attached to air bubbles do not report to the froth phase. Some of them detach from the bubble surface and drop back into the pulp phase. Tao (2) has shown that the probability of detachment (P_d) increases with increasing particle size D_p and increasing bubble size D_b. This conclusion is consistent with the empirical correlation established by Deglon et al. (11) which shows that the detachment rate constant for flotation increases with increasing D_b and D_p. Therefore, coarse particles are more likely to detach from air bubbles and use of small bubbles will decrease the probability of detachment.

Picobubbles normally refer to tiny bubbles smaller than 1 μm. Hydrodynamic cavitation is the process of creation of picobubbles in a liquid due to the rupture of a liquid-liquid or a liquid-solid interface under the influence of external forces. The work of cohesion of water (W_c) and the work of adhesion (W_a) between water and solid can be expressed in Equations (1) and (2):

$$W_c = 2\gamma_l \tag{1}$$

$$W_a = \gamma_l(1 + \cos\theta) \tag{2}$$

Obviously, the work of adhesion W_a is always smaller than the work of cohesion of water W_c, which indicates that cavitation will occur preferentially at the solid/water interface. In addition, since more hydrophobic particles have a greater contact angle θ, they will have a smaller value of W_c, indicating that hydrophobic particle surfaces are the favorable sites for cavitation to take place. Therefore, the generation of picobubbles by hydrodynamic cavitation is fundamentally a selective process, which should have a positive effect on flotation efficiency. The separation curves shown in Figs. 1b, 2b, 3b, 5b, and 6b obtained under different operating conditions all indicate that use of picobubbles significantly enhanced the separation efficiency.

The picobubbles generated on a hydrophobic particle surface by cavitation naturally attach to the particle, eliminating the collision and attachment process which is often the rate determining step for flotation of fine particles. Krasowska et al. (12) have demonstrated by recording bubble-particle collision images that when a tiny bubble exists on the particle surface, it is much easier for the particle to get attached to the large bubble. More efficient attachment of particles and improved flotation rate have been observed when tiny bubbles co-exist with air bubbles commonly used in flotation cells (13). Zhou et al. (3) showed that hydrodynamic cavitation significantly increased flotation kinetics of silica and zinc sulfide precipitates. Data shown in Fig. 1 to Fig. 6 unambiguously indicates that use of picobubbles increased the flotation recovery of fine coal particles. Figures 5 and 6 also show that use of picobubbles can significantly reduce the dosage of the frother and the collector. It is believed that picobubbles on the particle surface activate flotation by promoting the attachment of larger bubbles since attachment between picobubbles and large bubbles is more favored than bubble/solid attachment. In other words, picobubbles act as a secondary collector for particles, enhancing particle attachment probability and reducing the detachment probability. An earlier study by Attalla et al. (14) found that picobubbles generated with an acoustic method in coal flotation increased flotation yield by up to 15%, reduced the frother dosage by 10% and the collector dosage by 90%. Similar results were reported by Hart et al. (5) who performed statistically designed experiments on effects of picobubbles on coal flotation.

An issue of controversy related to picobubbles is the stability of the tiny bubbles. The Laplace equation suggests that for a spherical bubble of 0.1 μm diameter in water at 20°C, the capillary pressure is almost 30 atm, which makes it difficult to believe that picobubbles can be stable or metastable. However, there is much experimental evidence that suggests that picobubbles exist for at least several tens of minutes without discernible changes (15, 16). Observations of picobubbles have been reported by other investigators using a variety of techniques (17–20). The seeming inconsistence between the Laplace capillary pressure equation and the experimental evidences was explained by Attard (13) who postulated that

1. The nanobubbles are not in equilibrium with the gas-saturated liquid phase.
2. The microscopic contact angle is much larger than the macroscopic contact angle, and
3. The Laplace equation may not be applicable to nanosized bubbles.

Stockelhuber et al. (20) have developed a model to explain the liquid film rupture effect of nanobubbles at the collision of hydrophobic particles with air bubbles. Schubert (21) further claimed that the coalescence of nanobubbles on the hydrophobic particle with larger bubbles is responsible for the establishment of the three phase contact line at the attachment events in the flotation. The bubble-particle collision and attachment images published by Krasowska et al. (12) are in good agreement with this theory. It can be concluded from the above discussion that tiny bubbles such as picobubbles or nanobubbles play a huge role in the process of froth flotation.

CONCLUSIONS

The following conclusions can be drawn from the above results and discussion:

1. Laboratory flotation tests have shown that picobubbles significantly enhanced the coal flotation process efficiency with higher recovery and/or lower product ash.
2. The flotation recovery of fine coal was increased by 10 to 30 absolute percentage points, depending on the process operating conditions.
3. The collector dosage was reduced by one third to one half as a result of the adsorption of picobubbles on the particle surface. Adsorbed picobubbles have a stronger affinity to the hydrophobic solid surface than conventional-sized bubbles and can act as a strong secondary collector.
4. The frother dosage was also reduced by up to one half because picobubbles are mostly smaller than 1 μm when they are formed from air precipitation.
5. The improved flotation performance by picobubbles can be attributed to increased probabilities of collision and attachment and reduced probability of detachment.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the financial support from Kentucky Science and Engineering Foundation (KSEF) under Contract KSEF-148-502-03-69, which made this work possible.

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