ABSTRACT

Froth flotation is a widely used, cost effective fine coal cleaning process; however, its high process efficiency is limited to the narrow particle size range between 10 and 100 µm. Beyond this range, the efficiency of froth flotation decreases sharply, especially for difficult-to-float coal fines of weak hydrophobicity (e.g., oxidized coal).

Particle-bubble collision, attachment, and detachment are the most critical steps in the flotation process. It is known that the low flotation recovery of fine coal particles is mainly due to the low probability of bubble-particle collision. Fundamental analyses of froth flotation kinetics and hydrodynamics have concluded that use of smaller bubbles is the most effective approach to increase the probability of collision and maximize flotation recovery.

The main goal of this project was to enhance recovery of fine coal particles (-0.15 mm or -100 mesh), and particularly ultrafine particles (~44 µm or -325 mesh), using a flotation column or a mechanical flotation cell featuring a hydrodynamic cavitation picobubble generator or an air eductor for feed preconditioning. Picobubbles that are mostly smaller than 1 µm can be formed selectively on hydrophobic coal particles from dissolved air in fine coal slurry. They are characterized by an inherently high probability of collision with particles, a high probability of attachment, and a low probability of detachment due to their tiny size. Furthermore, they have a low ascending velocity, a low rebound velocity from the coal surface, and a high surface free energy to be satisfied. These characteristics make picobubbles very effective for enhancing flotation recovery of fine coal particles.

Results indicate that combustible recovery of a -100 mesh coal was increased by 20-50% for different size fractions and that flotation rate was increased by at least 41% in the presence of picobubbles. Other major advantages of the picobubble process include lower collector dosage and air consumption since picobubbles are produced from air naturally dissolved in water and they act as a secondary collector on particle surfaces, thereby resulting in considerably lower operating costs.
EXECUTIVE SUMMARY

The United States is one of the largest coal producing countries in the world with an annual clean coal production of more than 1.15 billion tons. Froth floatation is commonly used to clean -28 mesh (0.6 mm) or -100 mesh (0.15 mm) fine size coal. It is a physical separation process in which hydrophobic particles captured by air bubbles ascend to the top of the pulp zone and eventually report to the froth product whereas hydrophilic particles remain in the pulp and are discharged as tailings. This process is known to be more efficient and cost-effective than other fine particle separation techniques such as tabling, high gradient magnetic separation, and oil agglomeration. However, froth flotation is efficient only for particles within a narrow size range, normally from 10 to 100 µm. For ultrafine and relatively coarse coal particles (e.g., >1 mm), floatation performance declines. For example, flotation recovery for coal particles in the range of 10-100 µm may be as high as 90% whereas recovery of coal particles smaller than 5 µm may be only 20-30%, wasting a large portion of the valuable energy resource in coal fines. 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.

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

The present study was aimed at developing an innovative and practical technology based on improved understanding of froth flotation fundamentals to significantly improve the recovery of coal fines by integrating the picobubble technology into existing flotation devices such as mechanical and column flotation cells. The presence of picobubbles enhances the flotation process by increasing collision and attachment probabilities and decreasing the detachment probability. More significant improvement is expected with oxidized coal or other low hydrophobicity coal that is more difficult to recover by froth flotation.

A specially designed flotation column with a cavitation picobubble generator was manufactured and extensively tested for this project. Picobubbles were produced based on the hydrodynamic cavitation principle. Process parameters such as superficial feed rate, superficial air flow rate, superficial wash water flow rate, collector dosage, and frother dosage were studied for their effects on process efficiency. A mechanical flotation cell was also retrofitted to include a cavitation picobubble generator to demonstrate the feasibility and efficiency of the proposed process with mechanical flotation.
Major tasks performed during this study include: 1) Sample acquisition and characterization; 2) Fabrication of a specially designed flotation column integrated with a picobubble generator; 3) Monobubble microflotation experiments on flotation efficiency; 4) Column flotation experiments; 5) Mechanical flotation experiments; and 6) Technical and economic evaluations. Monobubble microflotation experiments were conducted to provide a better understanding of process variables on flotation efficiency and thus foster development of the innovative process to enhance fine coal recovery. Column and mechanical flotation experiments were performed to understand how primary operating parameters such as superficial gas velocity, superficial feed flow rate, wash water flow rate, collector dosage, and frother dosage affect cavitation picobubble enhanced flotation performance. A size-by-size analysis of flotation concentrate and tailings was conducted to determine separation efficiency for each size fraction under some conditions.

Results indicate that the combustible recovery of both -500 mesh coal and +200 mesh coal was increased by at least 15% and the flotation rate was increased by at least 200% in the presence of picobubbles. Other major advantages of the picobubble process include:

- Significantly expanded size range of particles that can be recovered effectively by froth flotation since picobubbles can greatly improve the collection efficiency of both ultrafine particles and relatively coarse particles.
- Reduced collector dosage by one-third to one-half due to the generation by cavitation of picobubbles on a particle surface, which act as a secondary collector. This is particularly important for ultrafine and oxidized coal samples since they normally require high dosages of reagents in conventional flotation processes.
- Increased flotation rate constant since smaller bubbles have a greater probability of collision with the particle and a lower probability of subsequent detachment. As a result, fewer flotation banks or columns are needed for a given feed stream, reducing capital and operating costs.
- Reduced air consumption since picobubbles are generated from air naturally dissolved in water. This also reduces operating costs.
- The ease of retrofitting an existing flotation machine with picobubble technology for immediate returns.

An economic analysis of at least 10% combustible recovery improvement achieved using picobubbles indicates that with a 100 ton/hr flotation feed rate of 35% average ash content, the total increase in flotation product achieving a 10% product ash requirement would be 7.2 ton/hr. At a selling price of $60/ton of clean coal and assuming 4000 operating hours per year, the annual increase in profits generated by picobubble application would be approximately $1.4 million. Based on these results, intensive efforts will be made to expedite the commercialization process with the next step being an on-site demonstration of the technology at the collaborating company’s commercial coal washing plant. Detailed, long-duration testing will be performed to evaluate performance and reliability of the process.
OBJECTIVES

The overall objective of this research program was to develop an innovative cavitation picobubble froth flotation process for improved recovery of fine coal particles (-0.15 mm or -100 mesh) by enhancing bubble-particle collision and attachment and minimizing detachment. Picobubble technology based on a Venturi cavitation tube was integrated into a column flotation cell to achieve the goal by feed preconditioning and/or tailing scavenging. Specific objectives of the project include:

1. Design and fabrication of a laboratory prototype flotation column of 2” diameter that is characterized by its dual bubble generators that produce both picobubbles (smaller than 1 μm) and regular sized bubbles (about 500 μm). The column has a capacity of about 1000 ml/min.

2. Evaluation of the innovative column flotation system for design features and performance limits as applied to cleaning Illinois coal.

3. Parametric investigation of the proposed technology to understand effects of process variables on separation performance with typical Illinois coal samples.

4. Economic evaluation of the proposed technology.

INTRODUCTION AND BACKGROUND

The flotation recovery of fine particles, particularly coal particles of poor floatability, can be enhanced by use of smaller bubbles to increase the probability of collection and adhesion and reduce the probability of detachment. An innovative cavitation picobubble enhanced froth flotation process was proposed for increased flotation recovery and reduced reagent consumption.

Cavitation picobubbles normally refer to tiny bubbles smaller than 1 μm. Hydrodynamic cavitation is the process for 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. Work of cohesion ($W_c$) of water and work of adhesion ($W_a$) between water and solid are described in Equations (1) and (2), where $\gamma_l$ is surface tension of the liquid (water) and $\theta$ is the contact angle.

$$W_c = 2\gamma_l$$  \hspace{1cm} (1)

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

Obviously, work of adhesion, $W_a$, is always smaller than work of cohesion of water, $W_c$, which indicates that cavitation occurs preferentially at the solid/water interface. In addition, since more hydrophobic particles have a greater contact angle, work of cohesion is smaller indicating that hydrophobic particle surfaces are favorable sites for cavitation to occur. Therefore, picobubble generation by hydrodynamic cavitation is fundamentally a selective process, which should have a positive effect on flotation efficiency.
Picobubbles attach more readily to particles than large bubbles due to their lower ascending velocity and rebound velocity from the surface and higher surface free energy to be satisfied. 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. It has been shown that the combined flotation by gas nuclei from air supersaturation and by mechanically generated bubbles produce higher flotation recovery than by either of them alone. Picobubbles on a particle surface activate flotation by promoting the attachment of larger bubbles (as shown in Figure 1) since attachment between picobubbles and large bubbles is more favorable than bubble/solid attachment. In other words, picobubbles act as a secondary collector for particles, reducing flotation collector dosage, enhancing particle attachment probability, and reducing the detachment probability. This leads to substantially improved flotation recovery of difficult-to-float coal particles and reduced reagent cost, which is often the largest single operating cost in commercial coal washing plants. Application of this process to coal flotation resulted in an increase in the overall flotation yield of up to 20% or higher, a collector dose reduction of 70%, and a frother dose reduction of 50% in preliminary studies. 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. Cavitation also improves the efficiency of coarse particle flotation by reducing the detachment probability during the rise of the particle-bubble aggregate. This is illustrated in Figure 2 where larger bubbles represent those produced by breaking the external air and smaller ones (picobubbles) are created by cavitation. While large bubbles may run away from the particle, cavitation bubbles, particularly those underneath the particle, will push the particle upward, facilitating particle recovery.

The Venturi tube shown in Figure 3 is the most widely used hydrodynamic cavitation device. Liquid flow accelerates in the conical convergent zone due to the narrowing diameter. The liquid in the cylindrical throat is higher in flow velocity and lower in pressure than liquid in the entrance cylinder, resulting in cavitation. The common presence of tiny pockets of
undissolved gasses in crevices of mineral particles assists the cavitation as a result of the expansion of these gas pockets under the negative pressure. The air eductor can also produce picobubbles based on a similar mechanism.

The key to the success of effective particle separation by flotation is the efficient capture of hydrophobic particles by air bubbles, which is accomplished in three distinct processes: collision, adhesion, and detachment.

The probability of collision \( (P_c) \) can be calculated from stream functions for quiescent conditions \([1, 2]\) and microturbulence models for well-mixed conditions \([3, 4]\). One of the mathematical models for \( P_c \) is shown in the following equation:

\[
P_c = \left[ \frac{3}{2} + \frac{4 \text{Re}^{0.72}}{15} \right] \left( \frac{D_p}{D_b} \right)^2,
\]

where \( D_b \) is the bubble size, \( D_p \) is the particle size, and \( \text{Re} \) is the Reynolds number. This equation shows that \( P_c \) increases with increasing particle size and decreasing bubble size. Fine particles have a low probability of collision with bubbles and are thus difficult to catch by bubbles, particularly by larger sized bubbles. This is the main reason for low flotation rates when processing fine particles.

The probability of attachment \( (P_a) \) is related to the energy barrier for the bubble-particle adhesion, \( E_1 \), and the kinetic energy of collision, \( E_k \), as shown in Equation (4) \([2, 5]\).

\[
P_a = \exp \left( -\frac{E_1}{E_k} \right)
\]

\( P_a \) can also be calculated using the following equation \([2]\):

\[
P_a = \sin^2 \left[ 2 \tan^{-1} \left( \frac{-45 + 8 \text{Re}^{0.72} u_b t_i}{15 D_b (D_b / D_p + 1)} \right) \right],
\]

where \( t_i \) is the induction time and \( u_b \) is the bubble rise velocity. Equation (5) indicates that \( P_a \) decreases with increasing \( D_p \), suggesting that coarse particles are more difficult to attach to air bubbles. \( P_a \) increases with increasing particle hydrophobicity or decreasing \( t_i \); \( P_a \) also increases with decreasing bubble size until the bubble size becomes too small.

All particles attached to air bubbles do not report to the froth phase. Some of them detach from bubble surfaces and drop back into the pulp phase. Particle detachment occurs when detachment forces exceed maximum adhesive forces. Adhesive forces include the capillary force, \( F_p \), and the excess force, \( F_e \), while detachment forces consist of the real weight of a particle in the liquid medium, \( F_w \), and the hydrodynamic drag force, \( F_d \). These forces are typically represented by the following equations \([6-9]\):
\[ F_p = \pi D_p \gamma (1 - \cos \theta_d) / 2; \quad (6) \]
\[ F_e = \frac{1}{4} \pi D_p^2 (1 - \cos \theta_d) \left( \frac{2 \gamma}{D_b} - \rho_w g D_b / 2 \right); \quad (7) \]
\[ F_w = \frac{1}{6} \pi D_p^3 \rho_p g - \frac{1}{8} \pi D_p^3 \rho_w g \left[ 2/3 + \cos(\theta_d / 2) - (1/3) \cos^3(\theta_d / 2) \right]; \quad (8) \]
\[ F_d = 3\pi D_p \eta \mu; \quad (9) \]

where \( \gamma \) is the liquid surface tension, \( \rho_p \) and \( \rho_w \) are densities of the particle and water respectively, \( \eta \) is dynamic viscosity of fluid, \( u \) is particle rising velocity, and \( \theta_d \) is the critical value of the three-phase contact angle right before detachment. It is very interesting to note that \( F_e \) increases with decreasing bubble size, \( D_b \), which means that smaller bubbles can be used to reduce coarse particle detachment. Therefore, flotation recovery of coarse particles can be enhanced using smaller rather than larger bubbles.

The probability of detachment \( (P_d) \) may be described by Equation \( (10) \) as follows:
\[ P_d = \frac{1}{1 + F_{at} / F_{de}}, \quad (10) \]

where \( F_{at} \) represents the total attachment force and \( F_{de} \) is the total detachment force. Using Equations \( (6) \) – \( (8) \) and neglecting the drag force, one obtains:
\[ \frac{F_{at}}{F_{de}} \approx \frac{3(1 - \cos \theta_d) \gamma}{g (\rho_p - \rho_w (1/2 + 3/4 \times \cos(\theta_d / 2)))} \left( 1 + \frac{D_p}{D_b} \right). \quad (11) \]

It can be readily seen from Equations \( (10) \) and \( (11) \) that \( F_{at}/F_{de} \) decreases and \( P_d \) increases with increasing \( D_p \) and increasing \( D_b \). This conclusion is in agreement with the empirical correlation that shows that the detachment rate constant for flotation increases with increasing \( D_b \) and \( D_p \) [10-12]. Therefore, coarse particles are more likely to detach from air bubbles and the use of small bubbles will increase flotation recovery of coarse particles.

The first order flotation rate constant \( (k) \) is determined by Equation \( (12) \) [12, 13]:
\[ k = \frac{3 V_g}{2 D_b} P = \frac{1}{4} S_b P = \frac{1}{4} S_b P_c P_a (1 - P_d), \quad (12) \]

where \( V_g \) is the superficial gas rate, \( P \) is the probability of collection, and \( S_b \) is the bubble surface area flux. Since \( P_c, P_a, \) and \( P_d \) are all dependent on \( D_b \) and \( D_p \), as discussed earlier, Equation \( (10) \) indicates that \( k \) is strongly dependent on \( D_b \) and \( D_p \). It has been shown that \( k \) varies as \( D_p^2 / D_b^3 \) under quiescent conditions in flotation columns. Obviously, the flotation recovery of particles can be enhanced effectively by use of smaller bubbles.
Based on the above scientific discussion, the following important conclusions can be drawn:

1. The low flotation recovery of fine particles is mainly caused by the low probability of bubble-particle collision; the main reason for poor flotation recovery of coarse particles is the high probability of detachment of particles from bubble surfaces.

2. The use of tiny bubbles such as picobubbles increases the probability of collision and adhesion and reduces the probability of detachment. In other words, smaller bubbles can be expected to enhance the flotation recovery of both ultrafine particles and relatively coarse particles, thus expanding the particle size range for effective froth flotation.

3. Larger bubbles are needed to provide sufficient levitation of coarse particle/bubble aggregates, which suggests that the simultaneous presence of small and large bubbles is necessary to treat feed slurries with a wide range of particle sizes.

**EXPERIMENTAL PROCEDURES**

**Particle Size Distribution Analysis**

A total of four 55-gallon drums of coal slurry were acquired from a mine in Illinois. The particle size distribution of the coal sample was measured by wet sieve analysis using the following sieves: 48 mesh, 100 mesh, 200 mesh, 325 mesh and 500 mesh. The different size fractions were filtered, dried, and weighed.

**Ash and Sulfur Analysis**

Additional characterization of the coal sample was performed by taking representative samples from tested samples, pulverizing them to 150 μm, and then analyzing them for ash and sulfur content.

**Release Analysis**

Release analysis is the procedure used to obtain the best possible separation performance achievable by any froth flotation process. As such, the performance of a flotation process can be monitored and improved with the aim of approaching this theoretically optimum flotation response given by the release analysis curve for a certain feed material. This goal is analogous to the gravity-based washability analysis. The release analysis test was carried out in a conventional laboratory flotation cell and conducted in two phases with distinctly different goals.

The first stage separates hydrophobic material away from hydrophilic material by doing multiple cleaning phases from the original feed. The sample was introduced into a laboratory Denver flotation cell of 5-liter capacity at a 5% feed solid content by weight. Collector (fuel oil) and frother (MIBC) were injected into the thoroughly mixed slurry at minimum doses. Fuel oil was added and the sample conditioned for five minutes prior to the addition of frother. Flotation was continuously performed in Phase I to float all the
hydrophobic material from the cell. When needed, frother was added to allow a continuation of flotation. The product was continuously collected in separate containers. When all of the floatable material was collected, the remaining material was placed in a different container which was labeled as tailings. The floated material was placed back into the flotation cell and refloated. This process was repeated three times to ensure the separation of all hydrophilic particles from hydrophobic particles.

The second stage has the goal of separating particles into fractions of different degrees of surface hydrophobicity. The more hydrophobic coal contains the least amount of ash-forming material with the ash content increasing with a decline in hydrophobicity. Fractionated samples are obtained by controlling air flow rate and rotator revolutions per minute (rpm) under starvation reagent conditions. Lower air flow rates and rotator rpm lead to higher floatable particles reporting first until no more particles are able to float (Concentrate 1). Then an incremental increase in air flow rate and/or rotator rpm was allowed to obtain the next most floatable particles with a larger amount of ash (Concentrate 2). A progressive increase in air rate or rotation speed assures the total flotation of the next set of more floatable particles by a fractionation process (Concentrates 3, 4, etc.). The process stops when no more particles can float. All concentrate samples were filtered, dried, weighed, and analyzed for ash content.

**Monobubble Microflotation**

The modified Hallimond tube was used to perform monobubble microflotation experiments with fine particles to investigate the effect of bubble size, particle size, and particle hydrophobicity on the flotation rate constant. The specially designed single bubble flotation setup is illustrated in Figure 4. The single bubble flotation apparatus consisted of a particle holder, a glass cylinder with a volume of approximately 1 liter, and a single bubble generator located at the bottom of the column. At the beginning of each experiment, clear water with varying concentrations

![Figure 3. Specially Designed Single Bubble Flotation Setup Used to Perform Microflotation Tests](image-url)
of frother was poured into the glass column from the top until the desired level was reached. Then compressed air was introduced into the single bubble generator to generate individual bubbles that rose in the frother solution. Particles in the holder were discharged into the frother solution when the single bubble had risen to a given location. Falling particles collided with the rising bubble, some of which were collected by the bubble and ascended to the frother solution surface. These experiments were performed under conditions both in the presence or absence of picobubbles.

**Flotation Column**

A cylindrical flotation column of 5 cm (2 inch) in diameter and 1.8 m (6 feet) in height shown in Figure 5 was utilized for coal flotation tests. The column was made of Plexiglas and featured a Venturi cavitation tube to produce picobubbles and a static mixer to produce conventional-sized bubbles.

The length of collection and froth zones typically used in the test program were 210 cm and 30 cm, respectively. With a diameter of 5.1 cm, the length-to-diameter ratio was around 51:1, which provided near plug-flow conditions. Wash water was added in the froth zone at a depth that was 1/3 of the froth zone height below the overflow lip.

The cavitation tube and the static mixer were used to generate picobubbles and conventional-sized bubbles, respectively. Both are compact and have no moving parts. The pipe diameter of the cavitation tube is 12 mm and the neck diameter is 3.2 mm. Frother was injected into the feed stream while air was injected into the stream prior to the static mixer. Feed slurry entered the column in the upper pulp zone, 45 cm below the overflow lip. After being fed into the column, coal particles collected by rising bubbles ascend to the top. Those that settle to the bottom of the column are pumped through the static mixer and the cavitation tube to have more chances for recovery.

The slurry jet comes out of the neck of the Venturi cavitation tube at a speed of 6 to 10 m/s causing hydrodynamic cavitation in the stream with picobubbles formed preferentially on coal particle surfaces. Picobubbles formed on hydrophobic coal particle surfaces remain
attached while those on hydrophilic particle detached, which was a selective process that enhanced flotation separation efficiency. Hydrophobic particles had higher collision probability with picobubbles, higher attachment probability, and lower detachment probability, as explained earlier, resulting in a greater flotation rate constant and flotation recovery. The slurry jet enters the column tangentially at the bottom. The total recycling flow rate through the static mixer is 11 L/min, which splits at a two-way connector into the cavitation tube and a pipe. As a result, the flow rate distribution (flow rate in cavitation tube/total flow rate in static mixer) can be adjusted to be 6.6 L/11.0 L = 60% (with picobubble) or 0 L/11.0 L = 0% (without picobubble). A microprocessor series 2600 Love Controls receives signals from a pressure transducer located at the bottom of the column. The signal adjusts the Miniflex pinch valve that controls the underflow flow rate and the desired froth level.

Prior to each test, feed slurry was conditioned for five minutes with fuel oil, which was used to enhance the hydrophobicity of coal particle surfaces. Conditioning was conducted in a sump that was equipped with a mixer and four baffles placed vertically and separated by an equal distance along the circumference of the sump. The feed slurry was pumped to a feed tank, which utilized a recirculating line to ensure suspension of all solids. A peristaltic pump was used to draw a pre-determined amount of feed into the flotation column. Unless otherwise specified, all column flotation tests were performed under the following conditions: froth depth of 30 cm; superficial gas flow rate of 0.5 cm/s; fuel oil collector dosage of 1.0 lb/ton; MIBC frother concentration of 30 ppm; superficial wash water flow rate of 0.12 cm/s; superficial feed slurry flow rate of 0.5 cm/s; feed slurry solids concentration of 7%. A period of time equivalent to three particle retention times was allowed to achieve steady-state conditions. After reaching the steady-state, samples of feed, product, and tailing streams were collected simultaneously. These samples were filtered, dried, weighed, and analyzed for ash content.

Major process parameters were examined individually to investigate their effects on flotation recovery and concentrate ash content with and without the cavitation tube. They include superficial gas velocity, frother dosage, collector dosage, superficial wash water flow rate, and superficial feed flow rate.

A size-by-size analysis of the flotation concentrate and tailings was conducted to determine flotation recovery and separation efficiency for each size fraction. Data from this analysis demonstrate how picobubbles affect flotation recovery and efficiency of different particle sizes, which can be further used for process simulation and performance prediction for different coal samples.

**Mechanical Cells Flotation Test**

To assess the impact of using picobubbles on coal separation performance, experiments were conducted with a bank of three 10-liter mechanical cells shown in Figure 6. During tests with picobubbles, part of the slurry in the third cell was pumped through a picobubble generator with 3.2 mm inner neck diameter and 12 mm inner pipe diameter, and then fed back to the first cell. In this configuration, picobubbles formed preferentially on hydrophobic coal particle surfaces remained attached while those produced on hydrophilic
particle surfaces detached, which was a selective process that enhanced flotation separation efficiency. Hydrophobic particles had higher collision probability with picobubbles, higher attachment probability, and lower detachment probability, as explained earlier, resulting in a greater flotation rate constant and higher flotation recovery.

Operating variables examined include flow rate to the cavitation tube, collector dosage, frother concentration, feed solids percentage, and feed slurry flow rate. Unless otherwise specified, all conventional flotation tests were performed under the following conditions: MIBC froth concentration of 20 ppm; fuel oil collector dosage of 0.49 kg/ton; flow rate to cavitation tube of 6000 ml/min; feed slurry solids concentration of 23%, and feed slurry flow rate of 2100 ml/min.

Kinetic flotation tests were also conducted to show the effect of picobubbles on flotation rate constants. Flotation performance data from these tests were compared to the release analysis data for a better understanding of effects of picobubbles.

**Technical and Economic Evaluation**

Detailed technical performance and economic feasibility evaluations were performed using data generated from column flotation and mechanical flotation experiments. Feed throughput, product ash, yield, combustible recovery, separation efficiency, and capital and operating costs were used for these evaluations.

**RESULTS AND DISCUSSION**

**Particle Size Distribution**

Table 1 shows the particle size distribution of tested coal sample as well as ash and sulfur content for each size fraction. It can be clearly seen from Table 1 and Figure 7 that ash content of the sample decreases as the particle size increases. This is the result of the concentration of fine clay particles in smaller size ranges. The overall feed ash content was 38.51%. Also, sulfur content decreases as particle size increases as shown in Table 1. The overall feed sulfur content was 2.99%.

Table 1 and Figure 7 indicate that the majority of coal particles (82.97%) were smaller than 150 microns (100 mesh). Also, 40.70% of coal particles were smaller than 25 microns (500 mesh).
**Table 1.** Size Analysis Data for Tested Coal Sample

<table>
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<tr>
<th>Particle size (mesh)</th>
<th>Elemental</th>
<th>Cumulative Passing</th>
<th>Cumulative Retained on</th>
</tr>
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<tbody>
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<td></td>
<td>Wt (%)</td>
<td>Ash (%)</td>
<td>Sulfur (%)</td>
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<td>72.87</td>
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<tr>
<td>Total</td>
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</table>

**Figure 6.** Particle Size, Ash, and Sulfur Distribution of Tested Coal Sample

**Release Analysis**

Figure 8 shows the flotation ash and ash rejection of the coal sample versus the combustible recovery and product yield. It can be seen from the figure that at the product ash content of 7.7% the product yield is 61.64%. The flotation combustible recovery and ash rejection at this product ash content are 93.37% and 87.86%, respectively while the ash content in the tailings is 89.46%.
Monobubble Microflotation

Figure 9 depicts the effect of picobubbles on the flotation efficiency of different size coal particles with varying bubble size at a given air flow rate. The figure indicates that the addition of picobubbles increased flotation efficiency, especially for 0.038-0.075 mm and 0.212-0.425 mm particles. During the experiment, it was also observed that picobubbles induced some fine particle coagulation which helped flotation. This effect was more significant with smaller particles.

Figure 10 shows the effect of picobubbles on the coal particle flotation probability at varying particle size when particle conditioning collector dosage was at 0.3 kg/ton. It indicates that the presence of picobubbles increased the coal flotation probability by up to 27%.
Figure 8. Coal Particle Flotation Efficiency Versus Bubble Size at a Given Air Flow Rate

Figure 9. Effect of Picobubbles on Flotation Probability of Varying Coal Particle Sizes at a Collector Dosage of 0.3 kg/ton
Flotation Column

Extensive evaluation of the effects of picobubbles on the flotation performance of a coal sample was carried out in a specially designed laboratory-scale flotation column. A number of flotation experiments were performed at varying collector dosage, frother concentration, superficial feed rate velocity, superficial air velocity, and superficial wash water velocity.

Effect of Collector Dosage on Flotation Performance With and Without Picobubbles

To investigate the influence of the collector dosage on flotation performance, different collector dosages of 0.07 kg/ton, 0.23 kg/ton, 0.49 kg/ton and 0.80 kg/ton were used. Figure 11 shows the effect of picobubbles on the combustible recovery and product ash at varying collector dosage. It can be seen that picobubbles substantially increased flotation recovery by about 5% to 10%.

Figure 11 also shows that picobubbles reduced collector dosage by one-half due to the generation by cavitation of picobubbles on particle surfaces, which act as a secondary collector. For example without picobubbles, the maximum combustible recovery was about 90% at 0.5 kg/ton collector, but with picobubbles, 90% combustible recovery was obtained at 0.25 kg/ton. This is particularly important for ultrafine and oxidized coal samples since they normally require high dosages of reagents in conventional flotation processes.

Increasing collector dosage further increased combustible recovery to about 94% in the presence of picobubbles but combustible recovery decreased to 84% in the absence of picobubbles. Product ash content was lower at 0.25 kg/ton collector dosage and higher at higher collector dosages in the presence of picobubbles than in their absence.

The combustible recover vs. ash rejection curve shown in Figure 12 indicates that the use of picobubbles significantly improved the separation efficiency since data points obtained with picobubbles are much closer to the upper right corner.

Figure 13 depicts the effect of picobubbles on the flotation efficiency of coal particles with varying collector dosage. It is clear from Figure 13 that the best separation efficiency was obtained at 0.3 kg/t in presence of picobubbles and 0.5 kg/t in absence of picobubbles.
Figure 10. Effect of Picobubbles on Combustible Recovery at Varying Collector Dosages

Figure 11. Ash Rejection vs. Combustible Recovery With and Without Picobubbles
Effect of Frother Concentration on Flotation Performance With and Without Picobubbles

To investigate the influence of the frother concentration on flotation performance, different frother concentration of 15 ppm, 30 ppm, 45 ppm, and 60 ppm were used. Figure 14 shows the effect of picobubbles on the combustible recovery and product ash at varying frother concentration. It can be seen that a significant improvement in combustible recovery of 5% to 7% was obtained in the presence of picobubbles.

Similar to the collector effect, picobubbles reduced frother concentration by one-third. For example, without picobubbles, maximum combustible recovery was about 89% at 55 ppm frother concentration, but with picobubbles 92.5% combustible recovery was obtained at 35 ppm frother concentration. Figure 14 shows that the product ash content was higher in the presence of picobubbles than in its absence.

The combustible recover vs. ash rejection curve shown in Figure 15 indicates that use of picobubbles significantly improved the separation efficiency since 96% combustible recovery was obtained at a high ash rejection of about 87%. Figure 16 depicts that picobubbles have a positive effect on the flotation efficiency of coal particles.
Figure 13. Effect of Picobubbles on Combustible Recovery at Varying Frother Concentrations

Figure 14. Ash Rejection vs. Combustible Recovery With and Without Picobubbles
To investigate the influence of the feed flow rate on flotation performance, different feed flow rates of 0.25 cm/s, 0.50 cm/s, 0.75 cm/s, 1.00 cm/s, and 1.25 cm/s were used. Picobubbles substantially increased flotation recovery as seen in Figure 17. For example, an increase of approximately 75%, i.e., from 20% to almost 95%, in combustible recovery was obtained at a superficial feed velocity of 0.5 cm/s in the presence of picobubbles. Although combustible recovery decreased from 95% to 55% when superficial feed velocity increased from 0.5 to 1 cm/s, it was still much higher in the presence of picobubbles than in their absence.

The product ash content was lower or almost the same in the presence of picobubbles than in their absence. The combustible recovery vs. ash rejection curve shown in Figure 18 indicates that use of picobubbles significantly improved the separation efficiency since data points obtained with picobubbles are much closer to the upper right corner. The separation efficiency vs. superficial feed velocity curve depicted in Figure 19 confirms that conclusion.
Figure 16. Effect of Picobubbles on Combustible Recovery at Varying Superficial Feed Velocities

Figure 17. Ash Rejection vs. Combustible Recovery With and Without Picobubbles
Effect of Superficial Air Velocity on Flotation Performance With and Without Picobubbles

To investigate the influence of the gas flow rate on flotation performance, different air flow rates of 0.4 cm/s, 0.8 cm/s, 1.2 cm/s, and 1.6 cm/s were used. Figure 20 shows the effect of picobubbles on combustible recovery and product ash at different superficial air velocities. When picobubbles were used, the flotation recovery was essentially unchanged when the superficial air velocity was increased from 0.4 to 1.6 cm/s. Product ash increased from 6.0% to 9.1% as superficial air velocity increased from 0.4 to 0.8 cm/s, then remained unchanged as superficial air velocity increased to 1.2 cm/s, and then increased another 3% as superficial air velocity increased to 1.6 cm/s. The great separation associated with high recovery and low product ash observed at low superficial air velocity was believed to be the result of good selectivity of cavitation generated picobubbles attaching to coal particles.

Combustible recovery was much lower in the absence of picobubbles at all superficial air velocities examined in Figure 21. For example, use of picobubbles increased combustible recovery by about 40% at a superficial air velocity of 0.8 or 1.2 cm/s. The combustible recovery vs. ash rejection curve shown in Figure 21 clearly indicate that use of picobubbles greatly improved separation efficiency of flotation, which is confirmed in Figure 22.
**Figure 19.** Effect of Picobubbles on Combustible Recovery at Varying Superficial Air Velocities

**Figure 20.** Ash Rejection vs. Combustible Recovery With and Without Picobubbles
Figure 21. Separation Efficiency vs. Superficial Air Velocity With and Without Picobubbles

Effect of Superficial Wash Water Velocity on Flotation Performance With and Without Picobubbles

Figures 23, 24, and 25 show the influence of wash water flow rate on column flotation performance. The wash water flow rate was set at 0 cm/s, 0.08 cm/s, 0.16 cm/s, 0.25 cm/s, and 0.33 cm/s. Wash water reduced both product ash content and combustible recovery as shown in Figure 23.

At all superficial wash water velocities, combustible recovery was substantially higher in the presence of picobubbles than in their absence while product ash was lower or essentially the same, which indicates once again that use of picobubbles improved the separation efficiency of column flotation, as confirmed in Figures 24 and 25.

Figures 26, 27, and 28 show flotation results obtained at 0.4 cm/s and 1.2 cm/s superficial air velocity with picobubbles at different wash water rates. Obviously, increasing air flow rate from 0.4 cm/s to 1.2 cm/s improved combustible recovery without compromising product quality, as shown in Figure 26. Figure 27 suggests that high superficial air velocity further improved separation efficiency since data points obtained at 1.2 cm/s were closer to the upper right corner, which is confirmed in Figure 28.
Figure 22. Effect of Picobubbles on Combustible Recovery at Varying Superficial Wash Water Velocities

Figure 23. Ash Rejection vs. Combustible Recovery With and Without Picobubbles
Figure 24. Separation Efficiency vs. Superficial Wash Water Velocity With and Without Picobubbles

Figure 25. Combustible Recovery and Product Ash vs. Superficial Wash Water Velocity with Picobubbles at 0.4 and 1.2 cm/s Superficial Air Velocity
Figure 26. Ash Rejection vs. Combustible Recovery with Picobubbles at 0.4 and 1.2 cm/s Superficial Air Velocity

Figure 27. Separation Efficiency vs. Superficial Wash Water Velocity With Picobubbles at 0.4 and 1.2 cm/s Superficial Air Velocity
Size-by-Size Study of Flotation Products

A size-by-size study of flotation products was conducted to assess the effect of picobubbles on coal flotation performance during laboratory picobubble enhanced coal flotation tests. Separation results are shown in Figures 29, 30, and 31 for three different size fractions, i.e., +200 mesh, -200+500 mesh, and -500 mesh and the overall feed.

Figure 29 shows product ash as a function of frother concentration. It can be seen from the figure that the presence of picobubbles increased the product ash content for all particle size fractions except -500 mesh, possibly as a result of higher recovery of middlings. For particles smaller than 500 mesh, picobubbles did not lead to an increase in product ash at any frother dosage except at 60 ppm at which product ash content was about 11.2% in the presence of picobubbles compared to 8.5% without picobubbles. For the overall feed, product ash decreased with increasing frother concentration as a result of more efficient separation with sufficient frother. The finer size fraction in the clean coal had higher ash content. This is mainly because feed ash in the finer size fraction was higher.

Results shown in Figure 30 indicate that combustible recovery in the -500 mesh and the +200 mesh size fractions increased by 15% in the presence of picobubbles at 30 ppm frother concentration. For the -200+500 mesh (-75+25 µm) size fraction, picobubbles had an insignificant effect on combustible recovery. The overall recovery was improved by about 10% at 30 ppm frother concentration and by 5% at the other frother concentrations.

Combustible recovery was higher for the -200+500 mesh size fraction at all frother concentrations indicating this size fraction of coal was easy to clean even with a low concentration of frother present in the slurry. However, for the coarser size fraction, combustible recovery increased sharply as frother concentration increased from 15 ppm to about 50 ppm. For the finer -500 mesh size fraction, combustible recovery decreased sharply as the frother concentration increased from 15 ppm to about 55 ppm.

The presence of picobubbles significantly increased combustible recovery for the coarser (+200 mesh) and the finer (-500 mesh) particle size fractions. Also, picobubbles slightly increased combustible recovery with increasing frother concentrations. This may be partly because the presence of picobubbles improved the flotation selectivity of all coal particles by increasing the probability of collision and the probability of attachment and by decreasing the probability of detachment of coal particles.

Figure 31 shows separation efficiency curves for different size fractions at different frother concentrations. The figure indicates once again that use of picobubbles improved the separation efficiency of the flotation process.
Figure 28. Product Ash vs. Frother Concentration for Different Size Fractions

Figure 29. Combustible Recovery vs. Frother Concentration for Different Size Fractions
Mechanical Cells Flotation Test

A three compartment Hazen Quinn (H-Q) conventional flotation cell with cavitation tube was used to investigate the benefit of picobubbles on the conventional mechanical flotation process. The total volume of the H-Q conventional flotation cell is 31 liters. With picobubbles, parameters tested include frother concentration, collector dosage, flow rate to cavitation tube, feed solid concentration, and feed flow rate. Baseline data were established from a kinetic flotation test using a 5-liter Denver flotation cell.

Frother concentration had a positive and significant effect on combustible recovery as shown in Figure 32 while the product ash was stable at 9%. The combustible recovery vs. product ash curve with picobubbles is compared to the baseline data curve without picobubbles in Figure 33. The separation efficiency vs frother concentration relationship is shown in Figure 34. Combustible recovery increased from 50% to 75% as frother concentration increased from 10 ppm to 40 ppm. Figure 34 shows that the highest separation efficiency was at 40 ppm frother concentration.

As collector dosage increased from 0.1 kg/ton to 0.9 kg/ton, combustible recovery increased from 45% to 70% as shown in Figure 35. Figure 36 shows the separation efficiency curve at different collector dosages. Figure 37 compares the combustible recovery vs. product ash curve with picobubbles to the base line data without picobubbles.
Figure 31. Combustible Recovery vs. Frother Concentration for H-Q Cell

Figure 32. Combustible Recovery vs. Product Ash (with Varying Frother Concentration) for H-Q Cell
Figure 334. Separation Efficiency vs. Frother Concentration for H-Q Cell

Figure 34. Combustible Recovery vs. Collector Dosage for H-Q Cell
Figure 35. Separation Efficiency vs. Collector Dosage for H-Q Cell

Figure 36. Combustible Recovery vs. Product Ash (with Varying Collector Dosage) For H-Q Cell
To investigate the influence flow rate to the cavitation tube has on flotation performance, cavitation tube flow rates of 2000 ml/min, 4000 ml/min, 6000 ml/min, and 8000 ml/min were evaluated. As flow rate increased from 2000 ml/min to 8000 ml/min, combustible recovery increased from 55% to 68% as shown in Figure 38. Also, product ash increased from 8% to 10%. Figure 39 shows the separation efficiency curve at different flow rates to the cavitation tube. Figure 40 compares the combustible recovery vs. product ash curve with picobubbles to baseline data without picobubbles.

Solids concentration has a slight influence on flotation performance. Figures 41 and 42 show that the best solids concentration is about 15%. Figure 43 compares the combustible recovery vs. product ash curve with picobubbles to baseline data without picobubbles.

From Figures 44 and 45, it can be seen that higher feed rates produced lower combustible recovery and product ash. From Figure 46, combustible recovery of about 89% was obtained at about 10% product ash and 80% ash rejection.

![Figure 37. Combustible Recovery vs. Flow Rate to Cavitation Tube for H-Q Cell](image-url)
Figure 38. Separation Efficiency vs. Flow Rate to Cavitation Tube for H-Q Cell

Figure 39. Combustible Recovery vs. Product Ash (with Varying Flow Rate to Cavitation Tube) for H-Q Cell
Figure 40. Combustible Recovery vs. Solids Concentration for H-Q Cell

Figure 41. Separation Efficiency vs. Solids Concentration for H-Q Cell
Figure 42. Combustible Recovery vs. Product Ash (with Varying Solids Concentration) for H-Q Cell

Figure 43. Combustible Recovery vs. Feed Flow Rate for H-Q Cell
Figure 44. Separation Efficiency vs. Feed Flow Rate for H-Q Cell

Figure 45. Combustible Recovery vs. Product Ash (with Varying Feed Flow Rate) for H-Q Cell
Effect of Picobubbles on Flotation Kinetics

With a Denver cell, batch flotation tests were conducted and kinetic flotation rates were calculated to show the effect of picobubble application. The flotation product was collected after 15, 30, 45, 60, 120, 240, and 480 seconds and samples were measured for their weight and ash content from which recovery was calculated. Results are plotted in Figure 47. These test results proved that flotation in the presence of picobubbles had a much higher combustible recovery and yield in a shorter time than flotation in the absence of picobubbles. The rate constant increased from 2.12 min\(^{-1}\) to 2.99 min\(^{-1}\) in the presence of picobubbles. In other words, picobubble application increased the kinetic flotation rate constant by 41%. Also, it is clear that product ash is lower in the presence of picobubbles than in their absence.

Flotation rate test results with picobubbles were much closer to the release analysis curve than those without picobubbles as shown in Figure 48. The curve closer to the upper left corner has the highest selectivity to recover coal particles by increasing collision and adhesion probabilities and reducing the detachment probability as mentioned earlier.

![Figure 46. Kinetic Rate Tests of Batch Flotation in a Denver Cell](image-url)
Comparison of Column Flotation Performance with Release Analysis

Figures 49 and 50 show the effect of picobubbles on combustible recovery in the product sample at a collector dosage of 0.49 kg/ton, frother concentration of 30 ppm, superficial wash water flow rate of 0.41 cm/s, and feed slurry solids concentration of 7%. Data for Figure 49 were generated by changing superficial slurry feed velocities from 0.25 cm/s to 1.23 cm/s while data for Figure 50 were generated by changing superficial gas velocities from 0.4 cm/s to 1.6 cm/s. It can be seen from these figures that the presence of picobubbles increased flotation combustible recovery by 35% to 70%. By comparing these combustible recovery curves in the presence of picobubbles and in the absence of picobubbles with the release analysis curve, it can be clearly seen that the flotation combustible recovery curves with picobubbles are much closer to the release analysis curve than those without picobubbles, indicating that the use of picobubbles considerably improved flotation combustible recovery.
Figure 48. Effect Of Picobubbles on Flotation Combustible Recovery at Different Superficial Feed Slurry Velocities

Figure 49. Effect of Picobubbles on Flotation Combustible Recovery at Different Superficial Air Velocities
Technical and Economic Evaluation

Depending on the type of flotation equipment used and characteristics of the coal being processed, the recovery improvement achieved with picobubbles varied from 35% up to more than 70%. To estimate the potential economic benefits of applying picobubbles in the flotation process, an economic evaluation was conducted.

The economic evaluation is based on assuming the average ash content of the feed is about 35% and the flotation feed is about 100 ton/hr. The cost associated with picobubble application includes operational and capital costs. The capital cost mainly includes Venturi tubes and an additional pump.

A 100 ton/hr flotation feed requires one bank of conventional cells, which can be either 4-compartment or 6-compartment with a processing capacity of 100 ton/hr. With a solids concentration of 10%, each conventional cell will have a flow rate of about 1000 m³/hr (0.278 m³/s). Compared to the laboratory scale Venturi tube, this flow rate is much larger; consequently, the Venturi size will be increased to avoid possible congestion. To minimize energy loss at the Venturi tube, feed with this high of a flow rate can be directed to flotation cells through multiple Venturi tubes. For the flow rate of 0.278 m³/s, 10 Venturi tubes can be used for each flotation bank, with the size of 2” at the throat and 4” at the cylindrical part. The pressure drop under this feed flow rate and Venturi tube is 88 Kpa, higher than the threshold value of 69 Kpa measured at the laboratory. Assuming each Venturi tube is $2000, the total cost associated with Venturi tubes is $20,000. The Venturi tube will last about three months and thus the annual cost will $80,000.

As the installation of Venturi tubes increases the resistance to the feed flow, an additional pump may be needed to maintain the flow rate. A Goulds Model JCU submersible slurry pump with a total flow rate of 4000 GPM or 0.25 m³/s can be used for this purpose. The current price for this model is about $15,000. Assuming the pump will last five years and allowing for inflation and warehousing costs, the annual cost will be approximately $5,000.

Therefore, total annual equipment cost will be $85,000. Considering a factor of 1.1 for miscellaneous accessories (including valves and flow meters) and a factor of 1.3 for installation cost, the total capital cost becomes about $121,550.

Based on our measurement with the laboratory picobubble generator, it is estimated that energy consumption will be increased by less than 5 kwh/ton of solids if the pump efficiency is 55%. Assuming the cost of the electricity is $0.12/kwh, the cost of electricity per year is $240,000 (=$0.12/kw x 5 kwh/ton x 4000 hours/year x 100 ton/hr). Thus, the total increase in costs for the picobubble application is $121,550 + $240,000 = $361,550 each year.

For the Illinois coal tested, the recovery improvement can be as great as 35% with column flotation. To make a conservative estimation, the recovery improvement for an industrial application is assumed to be 10%.
With 100 ton/hr flotation feed rate, 35% average ash content, 10% product ash requirement, and 10% combustible recovery improvement, the total increase in flotation product per hour would be:

\[ 100 \text{ ton/hr} \times (1-35\%) \times 10\%/ (1-10\%) = 7.2 \text{ ton/hr}. \]

At the current price for clean coal of about $60/ton, assuming 4000 working hr/year, the annual revenue generated by picobubble application would be:

\[ 7.2 \text{ ton/hr} \times 4000 \text{ hr/year} \times 60/\text{ton} = \$1,740,000. \]

Therefore, the net profit brought by picobubble application would be:

\[ \$1,740,000 - \$361,550 = \$1,378,450. \]

**CONCLUSIONS AND RECOMMENDATIONS**

**Conclusions**

Laboratory picobubble application to coal flotation has proven very successful. It not only significantly improved combustible recovery, but it also reduced reagent consumption. An economic evaluation has shown this technique is economically applicable, even for a plant with small processing capacity. Specific conclusions are:

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 75 absolute percentage points, depending on process operating conditions.

3. Collector dosage was reduced by one-half as a result of the adsorption of picobubbles on particle surfaces. Adsorbed picobubbles have a stronger affinity for hydrophobic solid surfaces than conventional-sized bubbles and can act as a strong secondary collector.

4. The frother dosage was also reduced by up to one-third 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.

6. Picobubbles improved flotation separation performance with coal particles in all size ranges, especially with ultrafine and relatively coarse coal particles.

7. Size-by-size analysis of column flotation products shows that picobubbles have a significant effect on improving the recovery of +200 mesh and -500 mesh particle size fractions. The improvement is about 15%.
8. Other optimal conditions for column flotation with picobubbles included a feed rate of 0.5 cm/s, an aeration rate of 0.5 cm/s with wash water rate of 0.1 cm/s (or aeration rate of 1.20 cm/s with wash water rate of 0.16 cm/s), frother concentration of 30-35 ppm, collector dosage 0.3 kg/ton, and slurry distribution ratio of 60% to the cavitation tube.

9. Picobubble application increased the kinetic flotation rate constant by 41%, which implies a significant increase in processing capacity.

10. For a coal washing plant with a 100 ton/hr feed rate to the flotation cell, the annual increase in profit from picobubble application is estimated at close to $1.4 million.

Recommendation

It is recommended that future work be conducted at a pilot-scale level to verify performance data obtained with the lab-scale column flotation unit used in this study. This work should be designed to achieve more reliable engineering data for the development of scale-up criteria for the technology prior to its eventual commercialization in the coal industry.

REFERENCES


DISCLAIMER STATEMENT

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