

IN-LINE STATIC MIXER FOR  
IMPROVED FLOTATION KINETICS

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INTRODUCTION

Conventional froth flotation is one of the most widely used mineral beneficiation processes. Unfortunately, long residence times are often required to achieve complete flotation (1). These slow flotation kinetics have been associated with the hydrodynamics within the flotation cell. While flotation cell manufacturers have optimized the mixing hydrodynamics, little effort has been made to improve the flotation hydrodynamics within the flotation cell (2).

A conventional flotation cell has both a turbulent region, where bubble-particle attachment occurs, and a quiescent region, where the ore-laden froth is removed from the cell (3). The flotation rate of a single particle in this environment is a function of the probabilities of bubble-particle collision, attachment, and the motion of the bubble moving to the froth (4). To increase the flotation rate of a flotation cell, the number of bubble-particle collisions must be increased. One way to increase the number of collisions is to increase the number of bubbles, either by decreasing the bubble size or by increasing the air flow rate to the flotation cell. Unfortunately, the bubble size is limited by the mechanical mechanism in a conventional cell, and at high air flow rates, the mechanical cell's agitation is less effective at breaking up the air into small bubbles. Another way to increase the number of collisions is to raise the turbulence within the cell by increasing the fluid velocity (2,3). Increasing the fluid velocity increases the relative velocities of the bubbles to the particles and improves the probability of bubble-particle collision. However, increasing the turbulence can also cause entrainment, where the bubble-particle aggregate gets carried out with the tailings. Increasing the turbulence can also cause detachment, where the flow conditions dislodge the particles from the bubbles. Thus, the process of attaching the particle to

the bubble and the subsequent separation of the bubble from the pulp interact significantly, in a conventional flotation cell, making it virtually impossible to optimize one of the processes without sacrificing the effectiveness of the other.

As a part of the Bureau of Mines' efforts to improve the efficiency of the domestic minerals industry, the Bureau has developed a rapid froth flotation system which separates flotation into two discrete unit operations: bubble-particle attachment and bubble-pulp separation (figure 1) (5). In the bubble-particle attachment unit, a bubble slurry is mixed with an ore slurry under highly turbulent conditions. The mixture is then rapidly fed into a quiescent bubble-pulp separation unit where the mineral laden bubbles are quickly separated from the pulp.

#### EXPERIMENTAL PROCEDURE

In this investigation, an in-line static mixer was evaluated as a bubble-particle attachment unit. The bubble slurry is pumped from a bubble generator. In the in-line static mixer, the bubbles and particles pass through each other at high velocities, causing rapid bubble-particle contact.

The froth-pulp mixture immediately enters the shallow-depth froth separator (figure 2). A sparger at the top of the unit disperses the froth-pulp mixture which provides the quiescent conditions necessary for adequate bubble-pulp separation. The relatively large diameter froth separator has a nominal depth of flow (approx. 2 cm) which minimizes the rising time of even the smallest bubbles (100  $\mu\text{m}$ ). As the material moved outward from the sparger, the ore-laden bubbles quickly rose to the top of the froth layer and overflow at the edge of the separator. The depth of this horizontal flow was fairly shallow, because the sparger distributes the pulp at the top of the separator. The effective volume of the froth separator was the disk shaped region at the top and was roughly equal to the surface area times the depth of the flow. Bubbles must rise out of the pulp during the time that the pulp is in this effective region. This time is referred to as the effective bubble residence time, because any bubbles that have not risen to the surface by the time the pulp reaches the outer edge of the froth separator will be swept down with the tailings as the pulp exits the unit. The effective bubble residence time becomes:

$$t_b = \frac{d_f \cdot A_s}{Q} \quad (1)$$

where  $d_f$  is the depth of the flow,  $A_s$  is the surface area of the froth separator, and  $Q$  is the volume flow rate. The effective volume largely depends upon the type of sparger used to distribute the flow radially. By using the same sparger throughout the test work, the effective depth remained relatively constant even as the flow rate varied. Therefore, for this research, the same sparger was used at every flow rate and with every froth separator. This kept the  $d_f$  relatively constant as the pulp radiated from the sparger. The unfloated pulp moved out the bottom of the unit.

Rapid flotation often requires multiple stages because adequate mineral recovery is not always obtained after one stage. In the second stage, the tailings product from the first stage was dewatered and again fed through the system for the second stage. This sequence was repeated for five stages. Beyond five stages, very little selectivity was obtained which resulted in a small improvement in copper recovery, but a large decrease in the overall concentrate grade. Therefore, for this study, only five flotation stages

were used. The concentrates from each stage were combined to form a final concentrate for the multi-stage flotation process.

To evaluate the effectiveness of the rapid flotation system, a western porphyry copper ore was tested to recover the copper. Conventional flotation tests were also carried out in a Denver<sup>1</sup> flotation cell in order to compare

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<sup>1</sup>Reference to specific products does not imply endorsement by the Bureau of Mines.

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the results with those obtained from the rapid flotation technique. The cell was set at 1,100 r/min and air was introduced at 4 L/min. Identical reagent and pH conditions were used. Timed samples of the flotation concentrate were taken to determine the flotation kinetics of the amine tailings sample in the Denver flotation cell.

The semi-continuous flotation system was designed to agitate the bubbles and ore pulp as they flowed through an in-line static mixer and to continuously remove the mineral laden bubbles from the ore pulp. The flotation system consisted of a slurry reservoir, a bubble generator, a bubble-particle attachment unit and a froth separator. The ore was conditioned with reagents in the slurry reservoir and pumped through the in-line static mixer along with the bubble slurry. The bubble pulp mixture, from the in-line static mixer, was then sent to the froth separator where the concentrate and tailings products were separated. The flotation process was continued until the ore slurry in the reservoir was depleted. At that time, 2 L of wash water was added to the ore reservoir to flush the system of any remaining ore. The concentrate and tailings were dried, weighed, and analyzed for copper.

The bubble generator was a conventional flotation cell (10 L) with the normal impeller replaced by a 16.5-cm-diam, high-speed spinning disk rotating at 3,300 r/min (6). Air striking the spinning disk was quickly transformed into small sized bubbles approximately 100  $\mu\text{m}$  size. These bubbles were significantly smaller than those generated in a conventional flotation cell.

The bubble-particle attachment unit was a 0.95-cm-diam, stainless steel pipe with a spiral insert which protruded 0.2 cm inward from the pipe wall. The spiral completed one revolution for every 0.5 cm of length throughout the 50-cm-length pipe.

Two different sized shallow-depth froth separators were employed. The bubble-pulp mixture entered the unit through a sparger which was centrally located near the top of the cone shaped tank. The bubbles quickly rose to the surface as the slurry spread out toward the sides of the unit. The froth overflowed at the outer edge and the tailings pulp drained out of the unit through the bottom. One unit had a 314  $\text{cm}^2$  surface area and a total volume of 1.7 L. The other unit had a 670  $\text{cm}^2$  surface area and a total volume of 5.2 L.

#### COPPER ORE FLOTATION

The in-line static mixer flotation system was tested with a western porphyry copper ore containing 0.67 pct copper. The flotation goal was to recover at least 90 pct of the copper from the ore in a concentrate of at least 5 pct copper.

The copper ore was obtained from a porphyry copper mine in Arizona. The major sulfide mineral was chalcopyrite with smaller amounts of pyrite. The

gangue was mostly plagioclase feldspar with smaller amounts of biotite and magnetite. The chalcopyrite was widely disseminated throughout the ore pieces and the liberation size was around 210  $\mu\text{m}$ .

The ore was ground with clear saturated lime water for 10 min in a laboratory rod mill at 70 pct solids and sized at 210  $\mu\text{m}$ . The plus 210  $\mu\text{m}$  size fraction was reground for an additional 8 min. The ground ore pulp was conditioned with 0.05 g/kg potassium amyl xanthate for 10 min in a stirred tank. Dowfroth 1012 frother was used to stabilize the bubbles. The water to ore ratio in the in-line static mixer bubble-particle attachment unit was equivalent to 25 pct solids for all the tests. At different aeration levels, the percent solids of the ore slurry was adjusted so that when combined with the bubble slurry, the percent solids in the in-line static mixer bubble-particle attachment unit was maintained at 25 pct solids. The conditioned sample was placed in the slurry reservoir and diluted to the proper percent solids. The conditioned ore pulp was then pumped through the in-line static mixer along with the bubble slurry. The flotation conditions are summarized in table I.

## EXPERIMENTAL RESULTS AND DISCUSSION

Flotation tests were designed to study the effect of mixing intensity in the in-line static mixer bubble-particle attachment unit, the residence time of the bubbles in the froth separator, and the air to ore ratio. Two different flow rates, 12 and 16 L/min were used to represent different mixing intensities within the in-line static mixer. Two froth separators with surface areas of 314 and 670  $\text{cm}^2$  were used to study the effect of residence time. Also, air to ore ratios of 0.25, 0.50, and 0.75 mL/g were tested in the in-line static mixer. The operating conditions for the copper flotation tests are shown in table II.

To determine the flotation rate, the first order kinetics equation was used:

$$\text{Recovery} = 100 - 100e^{-kt_r} \quad (2)$$

where  $k$  is the first order flotation rate constant and  $t_r$  is the total residence time of a particle in the flotation system. The sum of all the residence times for each flotation stage is included in the total residence time. Solving the equation for the flotation rate,

$$k = \frac{\ln\left(\frac{100}{100 - \text{Recovery}}\right)}{t_r} \quad (\text{min}^{-1}) \quad (3)$$

The speed of flotation among different tests would be reflected in the first order flotation rate constant calculated for each test. Equation 2 was used to calculate the flotation rate for both conventional and rapid flotation tests. Although the two tests were physically different, both closely approximated the first order kinetics equation. This provided a means to compare the two flotation systems.

Tests results, shown in table III, show that, for both separators and at all three air to ore ratios, the flotation rate and copper recovery were slightly higher at the high flow rate. The air to ore ratio had a statistically significant effect upon the copper recovery, obtaining the highest recoveries at the 0.75 air to ore ratio. The concentrate grade with the 670  $\text{cm}^2$  separator was significantly better than the grade with the smaller separator. The effective bubble residence time in the 670  $\text{cm}^2$  separator was

twice as long as the smaller separator. This allowed more of the gangue minerals to drain from the froth which produced a higher grade copper concentrate. The air to ore ratio had the largest effect upon the concentrate grade. The best concentrate grades were obtained at 0.5 air to ore ratio. At 0.75 air to ore ratio, the flotation rate of the gangue materials also increased which lowered the copper concentrate grade.

The flotation goal for this ore was to rapidly float 90 pct of the copper in a high-grade copper concentrate (greater than 5 pct Cu). The highest copper grade was obtained at the 0.50 mL/g air to ore ratio using the 670 cm<sup>2</sup> froth separators and the 12 L/min pulp flow rates. The fastest flotation rate, 2.01 min<sup>-1</sup> (table IV), was obtained at the 12 L/min pulp flow rate with the 314 cm<sup>2</sup> surface area froth separator. However, the 4.32 pct copper concentrate fell short of the established goal of 5 pct. Therefore, the best recovery (88.3 pct), grade (5.92 pct), and flotation rate (0.89 min<sup>-1</sup>) were attained at the 0.50 mL/g air to ore ratio at the 16 L/min pulp flow rate using the 314 cm<sup>2</sup> froth separator.

A comparison of the flotation results for the rapid flotation system to those of the conventional flotation system is shown in table V.

The rapid flotation system was over seven times faster than the conventional laboratory flotation cell. The capacity (tons per hour per cubic meter) of the rapid flotation system was over seven times greater than the conventional system. Therefore, a physically smaller rapid flotation unit could be used to replace a larger conventional flotation unit of the same capacity.

## CONCLUSIONS

The Bureau-developed rapid flotation system illustrates how the use of discrete units for bubble-particle attachment and bubble-pulp separation can improve the overall flotation kinetics. Each unit can be optimized to obtain the best performance of its function. There is an optimum mixing intensity and slurry residence time in the in-line static mixer bubble-particle attachment unit for the best performance. There is also an optimum froth separator surface area to flow rate ratio for the froth separator (effective bubble residence time). Matching these two optimized units would substantially improve the flotation kinetics. Improved flotation kinetics allow for much smaller flotation circuits to replace the larger conventional flotation circuits of the same capacity. Using the mixing intensity of the in-line static mixer bubble-particle attachment unit, air to ore ratio, and the froth separator surface area to flow rate ratio parameters, the rapid flotation system could be scaled-up.

The rapid flotation system was shown to be effective on a western porphyry copper ore containing 0.67 pct copper. The best copper grade was obtained at a 0.50 mL/g air to ore ratio, a 16 L/min pulp flow rate, with a 314 cm<sup>2</sup> surface area froth separator. About 88 pct copper was recovered from the ore in a rougher concentrate containing 5.9 pct copper at a rate over seven times faster than conventional flotation. These results were obtained using five flotation stages (2.4 min residence time).

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TABLE I.--Reagent and conditioning scheme for copper flotation

Ore charge.....g	1000
pH.....	12.5
Frothing agent.....	Dowfroth 1012
Frothing agent concentration...ppm	25
Air in bubble generator.....pct	35
Conditioning agent.....	Potassium amyl xanthate
Concentration.....g/kg	.05
Conditioning time.....min	10

TABLE II.--Operating conditions for copper flotation tests

Air/ore, mL/g	Total flow rate, L/min	Froth separator surface area, cm <sup>2</sup>	Mixing intensity power, W	Surface area to flow rate, cm <sup>2</sup> ·min/L
0.25	12	314	57	26
.25	12	670	75	56
.25	16	314	99	20
.25	16	670	104	42
.50	12	314	77	26
.50	12	670	75	56
.50	16	314	107	20
.50	16	670	114	42
.75	12	314	64	26
.75	12	670	75	56
.75	16	314	155	20
.75	16	670	104	42

TABLE III.--Flotation results at three different air to ore ratios, two pulp flow rates and using two different size froth separators

Air/ore, mL/g	Total flow rate, L/min	Froth separator surface area, cm <sup>2</sup>	Cu recovery, pct	Cu grade, pct	Total residence time, min	Flotation rate min <sup>-1</sup>
0.25	12	314	83.7	2.12	1.0	1.81
.25	12	670	84.4	3.36	1.3	1.43
.25	16	314	85.5	1.55	.5	3.86
.25	16	670	84.5	2.91	.9	2.07
.50	12	314	86.6	4.32	1.0	2.01
.50	12	670	86.0	7.92	3.5	.56
.50	16	314	88.3	5.92	2.4	.89
.50	16	670	87.0	7.70	3.3	.62
.75	12	314	88.3	3.00	.8	2.68
.75	12	670	87.5	3.77	1.1	1.89
.75	16	314	90.2	1.65	.5	4.65
.75	16	670	87.0	1.95	.9	2.27

TABLE IV.--Flotation results at the 0.50 mL/g air to ore ratio at 12 and 16 L/min pulp flow rates using the 314 and 670 cm<sup>2</sup> surface area froth separator

Froth separator surface area, cm <sup>2</sup>	Pulp flow rate, L/min	Copper recovery, pct	Copper grade, pct	Residence time, min	Flotation rate, min <sup>-1</sup>
314	12	86.6	4.32	1.0	2.01
314	16	88.3	5.92	2.4	.89
670	12	86.0	7.92	3.5	.56
670	16	87.0	7.70	3.3	.62

TABLE V.--Comparison of the rapid flotation system with conventional laboratory flotation

	Flotation system	
	Rapid	Conventional
Copper recovery.....pct	88.3	90
Concentrate grade.....pct	5.92	3.95
Residence time.....min	2.4	18
Rate of recovery.....min <sup>-1</sup>	.89	.13
Flotation capacity....t/h/m <sup>3</sup>	6.5	.89

Bubble-Particle Attachment Unit → Froth-Pulp Separator

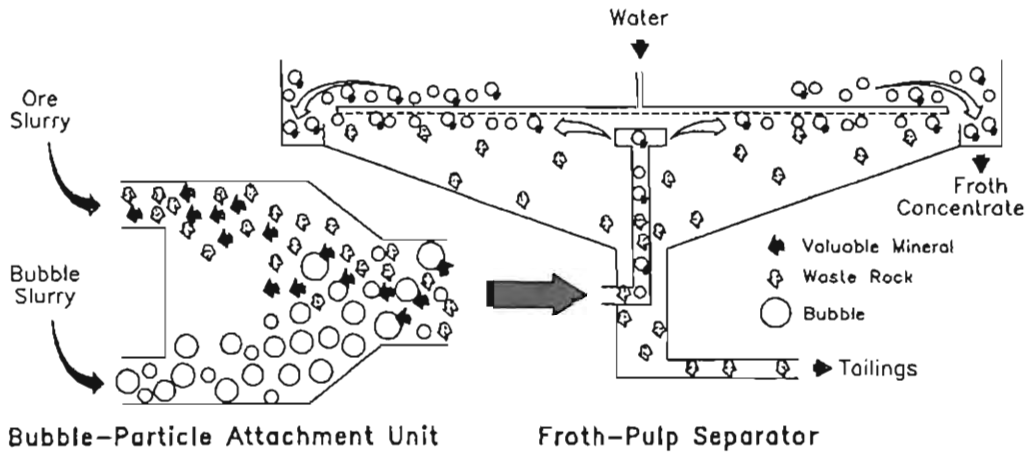


FIGURE 1.--Schematic diagram of the rapid flotation system.

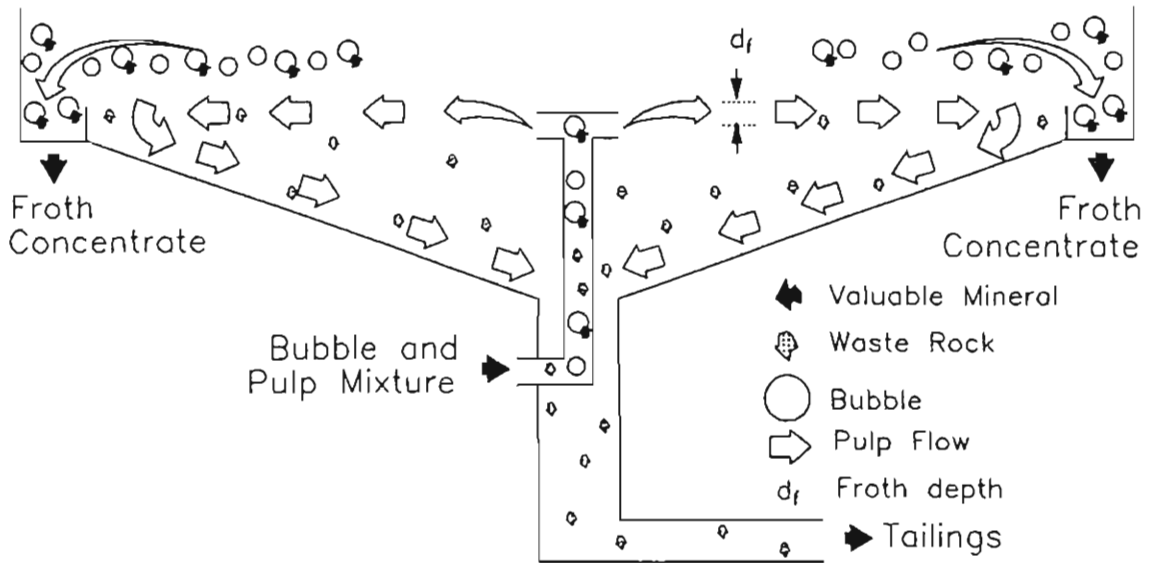


FIGURE 2.--Schematic diagram of the shallow-depth separator and slurry flow characteristics in the shallow-depth separator.

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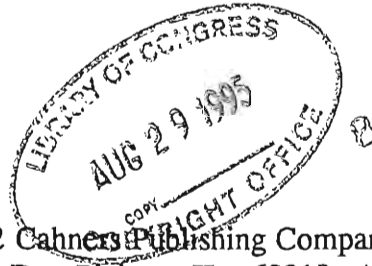
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