FLOTATION TECHNOLOGY FOR COARSE AND FINE PARTICLE RECOVERY

Eric Bain Wasmund, PhD, P.Eng
- Global Managing Director, EFD

I Congreso Internacional
De Flotacion De Minerales
Lima, Peru, Aug 2014

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This paper will discuss some of the current challenges associated with conventional froth flotation equipment, as well as solutions that can have a major impact on the industry world-wide. The Eriez Flotation Division's mission is to develop, install and support innovative flotation equipment solutions. EFD operates throughout the world, with offices in Canada, the USA, Brazil, Chile, Peru and Australia, and agents in Asia, Africa and Russia. To achieve this goal, EFD focuses on process expertise; almost half of our staff world-wide are process engineers, we have a large dedicated global test-lab for equipment sizing and flow-sheet development, and we focus on applications where conventional flotation is limited or not optimal.

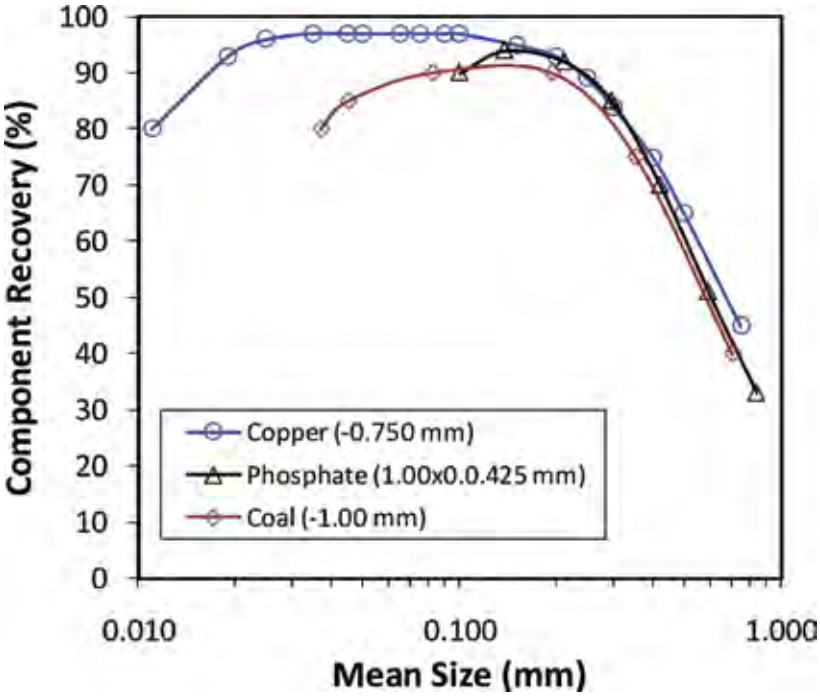

FIGURE 1
Flotation recovery by size for a variety of mineral systems

Figure 1, which has been adapted from the work of Gaudin et al (1931) and others, shows the metallurgical recovery by flotation of various pay-minerals by size class, including fertilizer materials, energy materials, and base metals. This illustration shows that conventional flotation technology is very well suited for the middle of the size range, but performance at either end of the size distribution suffers dramatically. There are two points to be made from this illustration. First, this is an ubiquitous phenomenon, and a wide range of diverse mineral industries are affected. Secondly, lower recoveries exist at the high range and the low range, so this problem cannot be addressed by adjusting the grind size. The basis of this problem has to do with the breadth of the size distribution that is produced by primary grinding and the limitations of conventional flotation to perform optimally across that range.

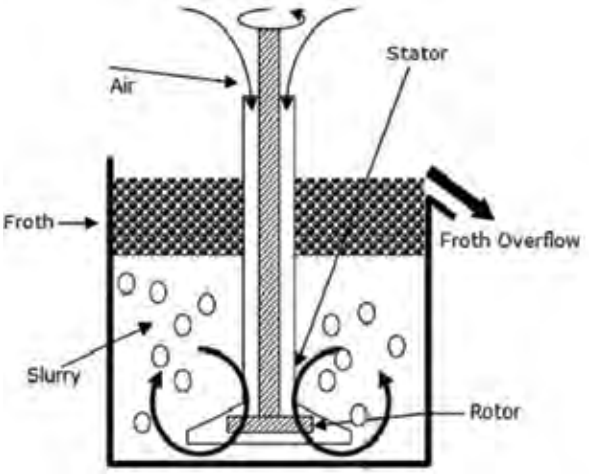

FIGURE 2
A simplified illustration of a typical mechanical flotation cell

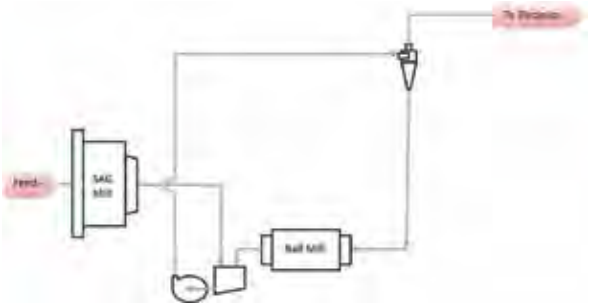

FIGURE 3
A simplified illustration of a primary grinding circuit used in mineral processing concentrators

Typical overall flotation recoveries in many of these industries is between 80-90%, and as shown, most of the losses in the remaining 10-20% will be contained in the fine fraction and the coarse fraction. Being able to economically recover a modest fraction of those losses would have a huge impact on a mine's bottom line, but more importantly, it can impact the world's economy and improve our global resource stewardship. As an example, considering copper alone, assuming an average loss of ~10%, the flotation loss described could amount to at least 1.5 million tonnes per year, with a cash value of $10 Billion.

To understand where there are opportunities for improvement, engineers should examine the technology that is used for the vast majority of froth flotation, especially in the rougher and scavenger applications: mechanically agitated cells. This includes self-aspirated cells such as the FLS Wemco, as well as designs where air is fed under pressure such as the Outotec TankCell®. A generic illustration of a conventional cell is shown as Figure 2. There has been a successful effort over the last 15 years to focus on designs that are upwardly scalable in size. This has been driven by the development of ore bodies with lower grade, and concentrators that have higher and higher name-plate capacities as described by Grönstrand et al (2010). Currently, there are commercial mechanical cells that are 500 m^3, which is more than 5 times larger than the largest cells from 25 years ago. Most of the innovation associated with this trend is around designing and building tanks, agitators and structures that can support the weight, forces, and harmonic loads of the larger installations. Metallurgical improvements on the whole have not occurred. The industry has been satisfied if the larger cells can be operated in such a way that they have the same or similar performance as a smaller cell of the same type (Grönstrand et al, 2010).

Mechanical agitation in a conventional cell achieves four functional objectives; keeping the pulp suspended (so the cell does not sand), shearing the incoming air into bubbles, adding enough turbulent energy into the pulp for bubbles and hydrophobic particles to mix and successfully collide to form bubble-particle aggregates, and providing a sufficiently quiescent fluid environment for the aggregates to rise into the froth and be carried over the launder. The optimal amount of shaft work will be different for each objective. For example, efficient collisions of fine ore particles with bubbles require high energy, while froth recovery generally requires low energy. The mechanical energy added into the cells is therefore a trade-off, and this is shown in the recovery by size curves of Figure 1.

Another proven approach is to perform size classification, and then process each stream using technology that has been designed and optimized for floating that specific size class. This is called a "split-feed flotation approach". In fact, size separation is already an essential part of the standard mineral concentrator, shown in Figure 3. In this configuration, feed from the primary mills feed a cyclone bank, with the overflow going on to flotation and the underflow forming a recycle stream back to the ball mill. A modification on this idea is to have one or more stages of size classification, followed directly by fines flotation and coarse flotation. A secondary benefit that the reagent conditioning can be optimized based on ore size. The split-feed flotation approach is utilized successfully throughout the world in mineral sectors such as coal and industrial minerals.

FIGURE 4
A cut-away of the Eriez HydroFloat® fluidized bed flotation machine

The first type of size-specific flotation machine that will be described is the HydroFloat®, a machine that was patented by Eriez in 2002 for floating coarse particles in a fluidized bed. Eriez has sold more than 40 of these units world-wide, mainly in the phosphate and potash industries, and is now focusing their attention on applications in gold and base metals. A cross-section of the unit is shown in Figure 4. The key is using fluidization water to form a stable liquid particulate fluidized bed. Feed enters at the top of the unit and flows down through the freeboard against the flux of fluidization water and entrained bubbles. From near the bottom of the bed, aerated fluidization water is injected uniformly across the cross-section of the bed through a manifold. Contacting between the bubbles and particles is optimized because of the high and uniform concentration of particles in the bed. As bubble-particle aggregates are formed, they are lifted out of the bed into the freeboard in a quiescent fluid environment, which reduces the phenomenon of aggregate detachment or drop-back. This is crucial, since it is well documented that bubble-particle detachment in the pulp and the froth, accounts for some of the lower recovery of coarse particles.

Because of the negative bias caused by the fluidization water, it is best when the fine fraction of the feed is removed or reduced prior to treatment in the HydroFloat. This is because fine particles or particles with low relative specific gravity can also be lifted into the freeboard if the upward drag force on the particle is greater than the downward force of gravity. For this reason, the HydroFloat is typically operated with a ratio of top size to bottom size of approximately 5:1. The occasion to classify the feed, also allows the fine fraction to be treated separately with technology that is more suitable for fine particle flotation.

Another difference between fluidized beds and mechanical cells is how the fluid and particles move within the unit. The residence time distributions inside mechanical cells have been modelled by CFD and measured by tracer studies and are generally shown to approximate the behavior of continuous stirred tank reactors (CSTR) as discussed by Froehling et al (2005). This implies that all material within the tank is well mixed, with some of the feed short-circuiting through the tank. Fluidized beds have been shown to have particle residence distributions closer to the plug-flow reactor (PFR) model type, meaning that the fluid moves together, with no axial mixing, and a more predictable flow path through the tank.

A recent study has been published that examines the performance of a lab-scale HydroFloat unit for flotation by size of a well characterized sphalerite (ZnS) ore (Awatey et al, 2013-2014). In this comparison, the feed was screened to remove minus 250 micron particles. The HydroFloat recovery by size was compared with a 1.5 liter Denver mechanical cell, under optimized and comparable conditions. In this evaluation, the HydroFloat outperformed the Denver cell for particles greater than 450 microns, and as expected, the recovery in the Denver cell continued to decline significantly as the particle size increased. According to the authors "this (result) is mainly due to the high degree of turbulence found within the conventional cell and the large froth barrier created by the pulp/froth interface, through which coarse particles traverse with only a low probability." It is note-worthy that flotation tests done in Denver lab cells are the industry-standard

FIGURE 5
A possible insertion point for the HydroFloat in a typical primary grinding circuit

benchmark for scaling up the flotation performance of mechanical cells and that plant results rarely, if ever, match the laboratory results.

Eriez has recently conducted the first stage of testing to evaluate the HydroFloat for treating cyclone underflow in a conventional large tonnage copper concentrator in South America. The idea is to insert the HydroFloat in the circuit as shown in Figure 5. Of course, this is a simplified flow-sheet, and other units such as screens, pebble crushers, de-watering units would have to be considered. A key question is whether the HydroFloat can economically recover enough coarse material to have a "throw-away tail", rather than recycling the high solids tail back to the ball mill or primary mill sump. This innovation could create some important possibilities;

1. The circulating load around the ball mill could be reduced by permanently removing the fraction of feed that goes to the HydroFloat
2. More feed could be put through the SAG mill, and
3. Certain metals with high SG and high ductility (poor grinding properties) such as free gold or native copper could be removed as product instead of getting trapped in the circulating load

In this test, feed was collected from within the milling circuit, specifically the cyclone underflow. The 80% passing size of the feed by mass was approximately 1000 microns and typically assayed at 0.4 to 0.6% copper. As has been observed elsewhere, about 10% by weight of the cyclone underflow sample was "misplaced fines", ie less than 100 microns. Approximately 70% by weight of the copper contained was greater than 100 microns and less than 850 microns.

This "feed" for the HydroFloat test was screened to exclude particles less than 180 microns and greater than 850 or 1000 microns. In practise, this double cut could be achieved many different ways, such as wet screens or with a wet screen and a teeter bed separator. The screened feed was floated in a 6 inch (150 mm) diameter lab HydroFloat, being fed at approximately 150 kg/hr with 1.5 m^3/hr of fluidization water. The resulting concentrate was enriched from 5 to 20 times with recoveries between 70 and 90%. A comparable test was not performed on a Denver cell, but considering the post-screened feed had a median size by weight of more than 400 microns, it is unlikely that any kind of mechanical cell could match this result as demonstrated in Figure 1.

Returning to the idea of the "split-feed flowsheet", the Eriez Flotation Division has also developed technology for preferentially floating fine particles. Following Sutherland (1948), the flotation recovery rate process is often described mathematically as the product of the probability of collision, the probability of attachment and the inverse of the probability of detachment. The probability of collision is often written as being proportional to the second power of the ratio of the particle size to the bubble size. In other words fine particles are not effectively collected by large bubbles. This is because smaller particles have lower inertia and are more likely to remain in the fluid streamlines that travel around the bubble's boundary layer. Larger particles, relative to bubble size, are less likely to track the fluid streamlines and will successfully collide with the bubble when they come in close proximity. As a result, gas spargers that produce smaller bubbles are preferred for collecting fine particles.

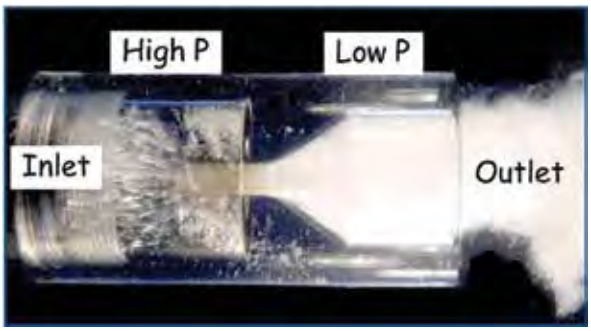

FIGURE 6
A clear plastic model of the CavTube being fed possible water and air

FIGURE 7
A model of a CavTube sparged column

The Cavitation-Tube® (CavTube), is a sparging device that achieves this objective. A clear plastic physical model is shown as Figure 6. In this device, a fluid, which typically consists of a liquid and gas mixture is pumped through a sudden contraction and expansion. As the compressed feed is expanded, bubbles on the order of 10^2 microns in size are formed by shearing apart large gas slugs. Additionally, as the local pressure exerted on the liquid drops, the concentration of dissolved gases like nitrogen and oxygen become supersaturated and can nucleate as fine bubbles the order of 1 micron in size. If the local pressure of the liquid drops below the vapor pressure, the liquid will also become supersaturated with respect to water vapor, resulting in cavitation. As with other super-saturation phenomenon, nucleation onto existing surfaces (heterogeneous nucleation) will take place preferentially over homogeneous nucleation, due to the additional energy required to create a new interface. So when ore slurry is pumped through an array of CavTubes, it is possible to create a bimodal bubble size distribution. Many of the fine bubbles will be tethered to the ore particles. This is illustrated nicely in the papers by Fan et al (2010).

A recent model study has clarified our understanding of the role of tethered microbubbles on the attachment of larger bubbles to hydrophobic surfaces. In this study, Krasowska and Malysa (2007) showed that surface roughness on hydrophobic particles allows the smaller microbubbles to attach to the surface, which subsequently decreases the time for a successful attachment of a large bubble to the same surface. As a result, heterogeneous nucleation of 1 micron bubbles onto ore surfaces significantly increases the rate of collection and attachment of those particles to larger bubbles which improves the capture rate (ie recovery). A combination of large and small bubbles therefore promotes the formation of stable particle-bubble aggregates. Assuming that nucleation of the fine bubbles is mostly a result of a super-saturation phenomenon that is determined by Henry's Law, it can be shown that the fine bubbles probably account for no more than about 2% by volume of all of the gas introduced through the spargers under typical column aerating. In other words, only a small volume of the micron-sized bubbles are required for this effect.

Eriez has sold more than 200 column flotation units using CavTubes for sparging and has retrofitted many other columns with this technology. In simplest terms, a stream from the column is extracted from the pulp phase, and pumped through a ring manifold containing CavTubes in parallel, which is recirculated back into the column. As the ore slurry is pumped through the array of CavTubes with added air, micron-sized bubbles are nucleated onto the ore surfaces and larger bubbles are also formed. This is illustrated in Figure 7. The mixture of larger bubbles and ore particles covered with micron-sized bubbles increases the collection efficiency in the column.

CavTubes can also be used to pre-aerate the feed for a flotation column, or any other type of flotation cell. In this case, the feed to a flotation cell is pumped through a manifold which feeds one or more CavTubes in parallel. The pre-aeration of the feed is independent of the air addition in the cell. In a lab-scale trial recovering coal using a column, pre-aerating the feed by sending it through a CavTube was shown to increase the carbon recovery, compared with the same test

conditions without feed pre-aeration (Honaker et al, 2011). Subsequent plant trials were conducted in a coal processing plant, looking at evaluating the pre-aeration technique on the feed stream to a train of three StackCells (Honaker et al, 2013). That study concluded that unit recoveries were increased and reagent consumption could be reduced. A study by Xu et al (2000) reported that recovery could be increased by pre-aerating through a Cavitation tube. In both of these studies, the positive benefit of preaeration existed without the addition of air and was even greater when extra air was added to the CavTube preaerator. This provides industrial evidence for the synergistic effect of having two size classes of bubbles for improving recovery. CavTube pre-aeration was also studied industrially for the reverse flotation of iron ore in columns (Alves et al, 2012). In this case, pure water was fed to the column inlet pipe through a CavTube array. A careful effort was made to keep the amount of added air and water the same for each set of experiments, to isolate the effect of pre-aeration from other variables such as J_g and percent solids. That report concluded that pre-aeration significantly increased unit recoveries.

Through these numerous examples, it is clear that industrial flotation rates and recoveries can be improved by selecting equipment and flow-sheets that take into consideration the physical properties of the ore. One of the most relevant of these properties is the size distribution. Industrial flotation over the last 100 years has been very successful at processing massive quantities of ore and efficiently recovering the majority of ore in the middle of the size range. There is now a great opportunity to go after the remaining 10-20%, which cannot be easily recovered with conventional technology. The Eriez Flotation Division is focusing on that opportunity. Working with customers and partners throughout the world, EFD has developed specific equipment such as the HydroFloat, CavTube sparged columns, pre-aeration and others, to specifically improve the flotation of coarse and fine particles.

ERIEZ
FLOTATION DIVISION

Eriez Flotation Division | Canada Inc
7168 Venture St
Delta, BC, V4G 1H6
Canada
Office: +1 604-952-2300
efdca@eriez.com

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