Innovations in the flotation of fine and coarse particles

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Abstract. Research on the mechanisms of particle-bubble interaction has provided valuable information on how to improve the flotation of fine (<20 µm) and coarse particles (>100 µm) with novel flotation machines which provide higher collision and attachment efficiencies of fine particles with bubbles and lower detachment of the coarse particles. Also, new grinding methods and technologies have reduced energy consumption in mining and produced better mineral liberation and therefore flotation performance.

1. Introduction

Flotation is an efficient and economical technique to separate valuable minerals from gangue minerals in an ore in the particle size range 10-500 µm. As the rich ore bodies are depleted, miners have to process large volumes of rocks to make the process viable, which can be easily handled by flotation by simply increasing the size of flotation cells (~700 m³). The separation by flotation is based on the difference in surface hydrophobicity of particles as they collide with gas bubbles (0.4-1 mm) in aqueous suspension in a flotation cell and only the hydrophobic particles attach to bubbles and rise to the top where they are recovered in the concentrate while the hydrophilic particles are sent to the tailings for further treatment. As most of the minerals are not naturally hydrophobic, short chain surfactants/collectors are added to selectively attach on and increase the surface hydrophobicity of the targeted minerals (usually the value minerals) while hydrophilic reagents, such as polymers, are added to depress the flotation of the unwanted minerals, and therefore further increase the mineral separation.

The flotation process involves the interaction between particles and bubbles which can be described by the three consecutive and independent sub-processes of particle-bubble collision, attachment and stability. The flotation rate constant and therefore the recovery is the product of the probability or efficiency of these sub-processes, particle-bubble collision (Eₐ), attachment (Eₐ) and stability (Eₛ=1-Eₐ), multiplied by the particle-bubble collision frequency [1]. Although the flotation outcome can be controlled by chemical factors (such as reagents type and concentration, pulp pH and Eh) which mainly affect the particle-bubble attachment/adhesion (Eₐ), flotation also depends on the hydrodynamic conditions in flotation cells such as agitation/turbulence which affects the particle-bubble collision frequency and detachment efficiency (Eₐ). Of course, particle-bubble collision frequency and therefore flotation rate and recovery depend on particles and bubbles number (wt% solids and gas flow rate, respectively) and their size while the intensity of agitation/turbulence affects the velocity and trajectory of particles and bubbles. A high agitation/turbulence in the flotation cell is
essential for maximum particle-bubble collision frequency; however, a high solids percent and/or attractive interaction between fine particles will increase the pulp viscosity resulting in decreased turbulent energy dissipation rate, which in turn has a negative effect on particle-bubble collision frequency. This was clearly demonstrated by Schubert [2] who showed that turbulence damping (decrease in the turbulent energy dissipation rate) occurs with increased volume percent of particles, especially with very fine particles (<1 µm) and their attraction. Addition of dispersants was found to restore the level of turbulence and improve the rheological properties of the suspension. A recent study has shown that a high feed solids percent of molybdenite particles decreased the flotation recovery of molybdenite but the addition of a dispersant restored molybdenite recovery [3]. It is likely that the high concentration of molybdenite particles and attraction between them have produced turbulence damping in the flotation cell which results in lower particle-bubble collision frequencies, and therefore lower flotation recoveries. Although a high agitation/turbulence in the flotation cell increases particle-bubble collision frequency and therefore flotation rate and recovery, too much turbulence is detrimental as the larger particles detach from the bubbles when the detachment force which can be simply represented by the centrifugal \( F_g = m \gamma \) and gravity forces \( F_g = m g \) becomes larger than the force of particle-bubble adhesion (proportional to the particle hydrophobicity or contact angle). As the centrifugal and gravity forces are proportional to the mass of the particle (density \( \pi \) diameter \(^3\)/6), the detachment force will increase with particle diameter and particle density, and correspondingly the flotation rate and recovery will decrease. Increasing the collector hydrocarbon chain length may increase the particle-bubble adhesion and therefore reduce particle detachment.

Conventional flotation machines were designed mostly for particles smaller than 150 µm, under which size most of the minerals in these particles are supposed to be liberated, and are most efficient for particles with sizes approximately between 10 and 150 µm [4]. Indeed, figure 1 shows typical recovery versus particle size curves for copper minerals along the bank of flotation cells. These curves present a recovery maximum at around 100 µm and a decrease in recovery for particles of smaller and larger sizes attributed to low particle-bubble collision efficiency and high detachment efficiency, respectively. The shape of these curves is common for all mechanical flotation machines independently of their size and the types of minerals floated [4] although the particle size of maximum recovery may slightly increase for lighter minerals (e.g., quartz) or decrease for denser minerals (e.g., galena), as shown in figure 2, as a result of an increased particle-bubble collision/attachment of the lighter minerals and detachment of the denser minerals. We note in the particular example in figure 1 that although the recovery of the finer particles is low in the first flotation cell it increases in the next flotation cells, which is characteristic of the slow flotation of fine particles [5] because of their low collision efficiency with bubbles (because of their low mass they follow the fluid streamlines around the bubble).

2. Diagnostic for the problem of low flotation

The analytical techniques of Scanning electron microscopy (SEM) and Quantitative evaluation of minerals by SEM (QEMSCAN) are used to inform on the degree of liberation of value minerals in particles which usually increases with decreasing particle size. These minerals are usually classified as liberated (90-100% liberation), middling (30-90%) or locked (0-30%). Larger particles are more likely to be composite particles where value minerals are locked. They have a relatively small proportion of their surface/volume made of value minerals covered with collectors and as a result their adhesion to bubbles is low and the detachment efficiency of these particles is high resulting in low recoveries. Figure 3 shows an example of two QEMSCAN images of particles in the size fraction +150-300 µm which clearly show that first most of the copper minerals in these particles are locked with gangue minerals and secondly the proportion of copper minerals in the particles is at least 30% in the concentrate and much less in the tailing. After collision, the air bubble spreads on the surface of a hydrophobic particle until an equilibrium contact angle is reached but for a composite particle the final contact angle on the hydrophobic domain is less than the equilibrium contact angle because the
perimeter of the bubble is pinned down at the interface between the hydrophobic and hydrophilic domains, which results in a weaker particle-bubble adhesion.

![Figure 1. Cu flotation recovery as a function of particle size in a copper ore [6].](image1)

**Figure 1.** Cu flotation recovery as a function of particle size in a copper ore [6].

![Figure 2. Flotation recovery of quartz, chalcopyrite and galena (density of 2.6, 4.3 and 7.6 g/cm³, respectively) as a function of particle size at 0.5 and 10 min. The vertical arrows show the change in recovery with increasing mineral density.](image2)

**Figure 2.** Flotation recovery of quartz, chalcopyrite and galena (density of 2.6, 4.3 and 7.6 g/cm³, respectively) as a function of particle size at 0.5 and 10 min. The vertical arrows show the change in recovery with increasing mineral density.
Figure 3. QEMSCAM images of particles in (left) the concentrate and (right) the tailing in the size fraction +150-300 \( \mu \)m in a copper ore [7].

Surface analysis of the particles can provide valuable information on the reasons why particles do not report to the concentrate, apart from the fact that they are composite particles. X-ray photoelectron spectroscopy (XPS), Time-of-flight secondary ion mass spectrometry (ToFSIMS) and Scanning Auger microscopy (SAM) are surface sensitive analytical techniques which can detect species on the top uppermost surface to a depth of 2 to 10 nm, and identify their chemistry and measure their concentration [8]. These surface species can be 1) the collector which can be in a too low concentration to provide enough hydrophobicity for a successful particle-bubble attachment; 2) fine gangue hydrophilic particles covering the value minerals, or slime coating, which need to be removed by chemical or mechanical methods (desliming) such as with charged polymeric and inorganic dispersants (e.g., carboxymethyl cellulose, carbonate, phosphate) or attritioning/high intensity conditioning. Figure 4 shows an example of the principle of ToFSIMS and its use to identify sphalerite and pyrite particles in a zinc ore after conditioning, and measure the species on their surface. The ToFSIMS total ion yield image shows all the particles present in the sample while the other images are only representative of a particular element, Zn and S (sphalerite), Fe and S (pyrite), Cu (copper activation of sphalerite) or IBX (collector isobutyl xanthate) on these particles. The Fe image shows clearly the three pyrite particles surrounded by the sphalerite particles while the other images show that more copper and IBX collector are adsorbed on the sphalerite than on the pyrite particles, which produces a good separation of these two minerals during flotation [8].

3. Solutions to the problem of low flotation
The causes for the low flotation of fine and coarse particles are different and therefore these particles require different chemical and hydrodynamic conditions during their conditioning and flotation [9]. For this, the feed is split up using size classification such as with cyclones so that each size fraction received the most appropriate technology. Fines have a much larger surface area than the coarse particles and therefore need more collectors. They also require higher agitation/turbulence to increase particle-bubble collision frequency and attachment efficiency while for coarser particles low agitation/turbulence prevents their detachment from bubbles. The use of fine bubbles (<100 \( \mu \)m, produced by electroflotation, hydrodynamic cavitation or gas supersaturation) has been shown to increase the collision efficiency of fine particles with these bubbles and therefore increase the flotation rate and recovery (due in part to a higher number of fine bubbles for the same air volume and their lower rise velocity) [10]. Aggregation of particles is also a solution to improve the low recovery of fine particles because particle-bubble collision efficiency increases with particle size [10]. However, particles aggregation is not particularly selective and gangue particles may be trapped in the aggregate. For coarse particles, existing flotation cells can be modified to restrict the recirculation of the so-formed particle-bubble aggregates in the high turbulence regions of the rotor, and therefore decrease particle detachment (froth crowders) [9].
New flotation cells have been developed to specifically address the problem of the low flotation of fine and coarse particles. For example, the HydroFloat™ uses an aerated dense fluidized-bed of particles where gas bubbles pass through the bed of particles and rise to the top with particles attached if the adhesion of the particle to the bubble and the buoyancy of the bubble are larger than the gravitation force [11]. With this set-up, shown in figure 5, there is maximum contact/collision between the gas bubbles and the particles, and no agitation/turbulence in this flotation cell and therefore particle detachment is reduced, which is particularly beneficial to the coarser particles. The flotation cells of type reactor-separator are more appropriate for the flotation of fine particles (figure 5). Air is injected at high pressure into the pulp in the confined space of the reactor, which insures optimum conditions to increase particle-bubble collision efficiency and frequency [12]. Moreover, the high pressure in the reactor (Reynold number of $10^4-10^5$) and its release in the separator (Reynold number of $10^2-10^3$) favour the nucleation of nano-bubbles only on the hydrophobic particles, which will further increase particle-bubble attachment. Results in Table 1 show that the reactor-separator produces a higher $P_2O_5$ recovery and grade compared to an Agitair mechanical flotation cell in the flotation of a phosphate ore.

Table 1. Difference in flotation performance between an Agitair and a Reactor-separator flotation cell.

| Flotation cell          | $P_2O_5$ recovery (%) | $P_2O_5$ grade (%) |
|------------------------|-----------------------|--------------------|
| Agitair                | 44.4                  | 28.4               |
| Reactor-separator      | 59.1                  | 32.9               |
As the rich ore bodies are depleted, particles have to be ground finer to liberate the values minerals disseminated in these particles, which leads to huge increase in energy cost (grinding accounts for around 40% of the total energy used in mineral processing operations and 4% of the world’s total electrical energy consumption [13]). Selecting the coarsest possible grind size reduces the overall grinding energy use. Floating coarse particles (such as with the HydroFloat™) allows to reject earlier those with no or little value minerals in them before further comminution in downstream processes of only those particles with economic interest. Reducing energy consumption can be achieved using new grinding methods such as with the High Pressure Grinding Rolls (HPGR) [9]. Also, high voltage pulses breakage technology, such as with SelfFrag, provides a better liberation of the minerals of interest in solids [14]. With this process, a more selective fragmentation occurs along grains boundary and at the interface of minerals composing the solid, which necessitates less energy during finer grinding and provides a more selective mineral separation in flotation.

4. References
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