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How gangue particle size can affect the recovery of ultrafine and fine particles during froth flotation

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ABSTRACT

In general, the poor flotation behavior of ultrafine (<10 μm) particles is mainly associated with a low particle/bubble collision efficiency within the flotation process due to an unfavorable particle/bubble size ratio. In those considerations the size of the gangue particles is usually not considered. This study investigates the effect of gangue particle size on the recovery of ultrafine and fine (10–50 μm) particles. Artificial, binary model particle systems, with magnetite as the target mineral and quartz as the gangue mineral, are used in this study in order to minimize reported issues associated with ultrafine gangue particles. Results indicate that ultrafine magnetite can be recovered similar to fine magnetite when the gangue particles are fine as well. In contrast, fine magnetite recovery drops significantly when ultrafine quartz is used as the gangue mineral system. This should thus open a discussion of a reconsideration of the collision efficiency models to incorporate the effect of the gangue particles.

1. Introduction

Froth flotation is one of the most widely used separation techniques in mineral processing. It is a heterocoagulation process where target mineral particles within an aqueous pulp selectively attach to air bubbles, forming particle/bubble aggregates, which are subsequently transported out of the pulp into a froth phase. All these sub-processes occur under appropriate hydrodynamic conditions. As the air bubbles mainly differentiate between hydrophobic and hydrophilic surface properties, the process selectivity is essentially based on differences in wetting properties of the solid particles suspended in the pulp (Wills and Finch, 2016; Schubert, 1996; Laskowski, 1992). Therefore, selectively rendering the surface of the target particles hydrophobic through adsorption of collector molecules plays a key role for the achievable process response, besides appropriate hydrodynamic conditions and sufficient surface liberation. As a consequence, it can be emphasized that the froth flotation process is marked by several different sub-processes, which occur within the pulp phase as well as in the froth phase. Even though its basic principles are quite well understood, it is difficult to quantitatively predict the process result in terms of recovery and grade due to the complexity of the different sub-processes able to act either independently, synergistically or antagonistically. In order to describe the flotation response a probabilistic approach is suggested in literature (Nguyen and Schulze, 2003; Pyke et al., 2003; Yoon, 2000; Ahmed and Jameson, 1989; Dobby and Finch, 1987; Trahar, 1981). In doing so, the efficiency of particle/bubble collection is mainly determined by a sequence of efficiencies of main sub-processes occurring within a flotation device. The summation of each efficiency stands then for the overall flotation response. With respect to the pulp phase, the main sub-processes are considered to be the particle/bubble collision efficiency, the particle/bubble attachment efficiency and the particle/bubble aggregate stability (Nguyen and Schulze, 2003; Yoon, 2000; Trahar, 1981). The efficiency of collision is largely influenced by the hydrodynamic conditions of the flotation process. The attachment efficiency, on the other hand, is mostly determined by the surface properties of the solid particles, including wettability as well as shape and roughness (Guven et al., 2015). Aggregate stability is influenced by both surface and hydrodynamic properties (Pyke et al., 2003; Yoon, 2000). Thus, the recovery of target particles during flotation is determined by the efficiency of collision as well as the particle/bubble aggregate stability, whereas the efficiency of attachment is mainly responsible for process selectivity (Yoon, 2000; Dobby and Finch, 1987), as not all particles colliding with air bubbles result in a flotation event.

One of the often discussed phenomena of the flotation process is the influence of the particle size to the flotation response. There

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is a typical particle size/recovery relationship observed in many investigations. The flotation process works best in a quite narrow particle size range (approximately 10–100 μm) (Jameson, 2012; Schubert, 2008; Trahar, 1981). Recovery decreases with increasing particle size, because of an increased probability of particle/bubble detachment during the process (Nguyen and Schulze, 2003). Furthermore, processing particle systems with increased percentages of ultrafine particles (<10 μm) usually results in rather inefficient process performances, namely poor recovery and low grade (Leistner et al., 2016; Sivamohan, 1990; Trahar and Warren, 1976). It is assumed that the lower probability of collision between air bubbles and ultrafine particles is one of the main reasons for the poor recovery (Trahar, 1981). Nevertheless, there exist different reported values for lower flotation particle size limits for different minerals (Trahar and Warren, 1976) as well as examples where ultrafine particles have been very well recovered (Trahar, 1981; Meloy, 1962). Many approaches, which are reported in literature, aim at modelling the efficiency of particle/bubble collisions during flotation (Koh and Schwarz, 2003; Dai et al., 2000), which will not be detailed here. As flotation cells mainly operate under intense turbulent conditions, the different modelling approaches use simplifications in order to describe the particle/bubble collision efficiency. One assumption most authors agree on is that ultrafine particles, due to their small size, and thus, small mass, are rather following fluid streamlines around air bubbles instead of colliding with them. As such, the efficiency of collision is set in relation with the ratio of particle size (of the target particles) and size of the air bubbles (Dai et al., 2000; Trahar and Warren, 1976). Decreasing target particle size causes an inappropriate particle/bubble size ratio, and thus, lowering the efficiency of collision, which leads to lower flotation rates for ultrafine particles. Several studies report a linear relationship between flotation rates and target particle sizes (Ahmed and Jameson, 1989; Trahar, 1981). Thus, it is concluded that flotation rate constants could be used as a measure for particle size effects (Jameson, 2012). Processing strategies trying to increase the collection efficiency for ultrafine particles, therefore, basically aim at intensifying hydrodynamic conditions combined with separate treatment of particle size fractions (Jameson, 2010; Schubert, 2008; Ahmed and Jameson, 1989; Trahar and Warren, 1976), decreasing air bubble size (Solari and Gochin, 1992; Sastry, 1979; Trahar and Warren, 1976), selectively enlarging target particle size (Leistner et al., 2016; Forbes, 2011; Subrahmanyam and Forssberg, 1990; Warren, 1975; Schubert et al., 1966), increasing particle/bubble wettability (Yoon et al., 1992) or the use of oil or oily carriers instead of pure air bubbles (Leistner et al., 2014; Liu et al., 2002; Shergold, 1982).

To our knowledge, gangue particle sizes do not play any significant role in the models for particle/bubble collision efficiency reported in literature. Except a negative impact on pulp rheology in the case of higher solid contents (Weiss and Schubert, 1988; Schubert, 1999), through an increase of pulp viscosity, and thus, decrease of turbulence intensity and energy dissipation, gangue particles are not incorporated into collision efficiency models. Reported recovery and grade issues associated with ultrafine gangue particles are (Wills and Finch, 2016; Sivamohan, 1990; Trahar, 1981):

- Unselective transport into the froth zone through entrainment and entrapment,
- Increase froth formation and stability,
- Contamination of the aqueous pulp phase due to an increased dissolution of disturbing ions followed by collector passivation through ion/collector interaction and/or precipitation on mineral surfaces,
- Unselective collector adsorption due to high surface free energies and
- Slime coating of target and gangue particles and air bubbles.

In this paper an investigation on the effect of gangue particle size on the recovery of fine (10–50 μm) and ultrafine (<10 μm) target particles during froth flotation is conducted. The investigation builds on the findings described in the work of Weiss and Schubert, 1988. Artificial, binary model particle systems and carefully chosen process conditions are used for the flotation experiments, in order to considerably minimize issues associated with ultrafine gangue particles. Results unveil contradictions on particle/bubble collision efficiency considerations which are critically discussed.

2. Experimental approach

2.1. Minerals and chemicals

The minerals chosen to generate the binary model particle systems for the flotation experiments are magnetite (MAG), as the target mineral, and quartz (QRZ), as the gangue mineral. The MAG sample is from an unknown location. XRD analysis yielded 80% Fe_3O_4, 17% Fe_2O_3 and 3% SiO_2 as constituents. The QRZ sample is high purity silica sand processed by iron-free grinding (brand-name: “Millisil®”), obtained from the Quarzwerke Group GmbH, Germany. XRD analysis yielded >99% SiO_2. From each mineral, two size fractions are generated for the experiments, a fine (10–50 μm) and an ultrafine (<10 μm) fraction. The MAG sample is representatively split into two fractions. One can be readily used as the fine fraction MAG(f), while the other one is ground to approximately 80% passing 10 μm using a planetary ball mill providing the ultrafine fraction MAG(uf). The QRZ sample is also split into an ultrafine fraction QRZ(uf) and a fine fraction QRZ(f) using air classification. The particle size distributions for the single mineral fractions are determined by laser diffraction (Sympatec HELOS) and are depicted in Fig. 1. Additionally, granulometric parameters, namely the particle size distribution parameters D_{10}, D_{50} and D_{90}, mean particle diameter D_m, Sauter mean diameter D_{32}, the amount of ultrafine (<10 μm) particles $Q_3(D = 10\ \mu m)$ and the specific surface areas $S_{m,calc}$ (obtained by laser diffraction) and $S_{m,BET}$ (obtained by BET adsorption analysis), of the four mineral particle size fractions are given in Table 1.

Flotation reagents include sodium oleate (NaOl) from Carl Roth as the collector, 4-Methyl-2-pentanol (MIBC) from Sigma Aldrich as the frother, and aqueous solutions of hydrochloric acid (HCl)

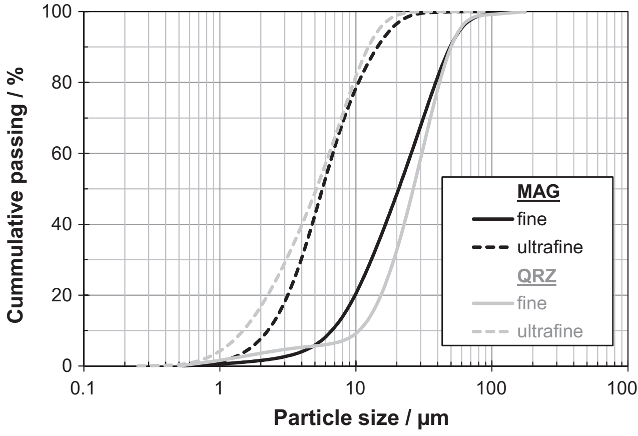

Fig. 1. Particle size distribution of the four different mineral size fractions (obtained from laser diffraction analysis), fine magnetite MAG(f), fine quartz QRZ(f), ultrafine magnetite MAG(uf) and ultrafine quartz QRZ(uf), which were used to generate the different feed particle systems f-f, f-uf, uf-f and uf-uf for the flotation testwork.