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Detachment of coarse composite sphalerite particles from bubbles in flotation: Influence of xanthate collector type and concentration

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The force required to detach sphalerite ore particles from air bubbles has been measured in flotation concentrates, for particles in the size range of 150–300 μm and 300–600 μm with different degrees of liberation. An electro-acoustic vibrating apparatus, that produces typical force conditions experienced in a flotation cell, was used to measure particle–bubble detachment as a function of the vibrational acceleration. Sodium isopropyl xanthate (SIPX) and potassium amyl xanthate (PAX) collectors were used in flotation, at different concentrations. At a fixed frequency of 50 Hz, the maximum vibrational amplitude at which a particle detaches from bubble was used to calculate the particle detachment force. It was shown that changes in surface hydrophobicity (contact angle), due to variations in reagent conditions have significant impact on particles detaching from bubbles. On average, detachment of particles from oscillating bubble correlated well with xanthate concentration and hydrocarbon chain length of xanthate ions. Particles (300–600 μm) with high contact angle obviously required higher force to detach from bubbles than similar particles with lower contact angle. This correlated well with the flotation response at the different reagent conditions. SEM analysis of particles after detachment showed that fully liberated particles attached to bubbles more readily and also gave higher detachment force than composite particles. Moreover larger detachment forces were observed, on average, for particles with irregular shape compared to particles with rounded shape of the same size range.

1. Introduction

Concentration of minerals by froth flotation demands crushing and grinding to liberate the mineral of interest before flotation. Perfect liberation is never achieved practically (Meloy, 1984; Wen Qi et al., 1992). However, both liberated particles and particles of "locked" minerals and gangue, known as composite particles (Sutherland, 1989; Wills and Napier-Munn, 2008; Wang and Fornasiero, 2010), are produced. Even though coarse and composite particle flotation provides opportunities for reducing the grinding cost and an increased throughput advantage, their floatability is complicated by their high inertia and potentially low hydrophobicity.

Mineral flotation is a size dependent process; fine, intermediate and coarse particles show different flotation behaviour. It has been reported that efficient flotation of mineral particles occurs for particle diameters in the range of 10–150 μm (Shergold, 1984; Nishkov and Pugh, 1989). Below the lower and upper limit of this size range, there is low or poor recovery of mineral particles. The low flotation recovery of fine particles is due to low collision efficiency between the particles and the bubbles, whilst the decrease in recovery for coarse particles (greater than 100 μm) is known to be due to detachment of particles from bubbles. The detachment of particles from bubbles is caused by bubble oscillations, gravitational forces and turbulent forces in the turbulent environment of an agitated flotation cell (Trahar and Warren, 1976; Holtham and Cheng, 1991; Schubert, 1999; Pyke et al., 2003; Gontijo et al., 2007; Dai et al., 2000).

Bubble-particle detachment of coarse particle, may also be attributed to low surface hydrophobicity as in the case of composite particles, with the hydrophilic mineral phases causing the particles to behave as if they had a reduced contact angle (Prestidge and Ralston, 1995). In practice, locked minerals particles in coarser size fractions contribute to valuable mineral loss in many mineral processing plants (Sutherland, 1989). An appreciable flotation response of coarse and composite particles is mostly dependent on the stability of the particle-bubble aggregate in the turbulent region of the flotation cell (Schulze, 1977) and also the differences in degree locking of the hydrophobic mineral, either completely locked or partially exposed in hydrophilic mineral phase (Wang and Fornasiero, 2010). Getting an efficient reagent adsorption

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concentration to control the overall mineral surface hydrophobicity will considerably improve the flotation of valuable mineral. In spite of surface modifications, the floatability of the valuable mineral is particle size dependent, with fine and coarse particles requiring more collector (i.e., higher hydrophobicity) to float for hydrodynamic reasons (Boulton et al., 2003) in the case of sulphide minerals.

The present work seeks to study the particle-bubble detachment for coarse composite sphalerite particles using a novel vibrational apparatus, at varying collector concentrations. In this work, the use of two different collectors with different carbon chains (sodium isopropyl xanthate and potassium amyl xanthate) was employed to study the effect on the detachment of particles.

2. Theory and principles

A mineral particle will suffer detachment from bubble if the force of detachment (F_{det}) is greater than the maximum force of attachment (F_{att}). At equilibrium, the balance of forces is:

$$F_{det} = F_{att} \tag{1}$$

Considering a single spherical particle at a gas–liquid interface, the maximum attachment force can be expressed as an approximation given by Eq. (2) (Nutt, 1960):

$$F_{att} = \pi\sigma\frac{d_p}{2}(1 - \cos\theta) \tag{2}$$

where d_p is the particle diameter, σ is the liquid surface tension and θ is the three phase contact angle. Eq. (2) is also referred to as the capillary force (Drzymala, 1994; Tao, 2005). There are other forces acting between particle and bubble, such as hydrostatic pressure and excessive force (Drzymala, 1994), which is the difference between the excess pressures on the bubble favouring attachment. It is common practice to neglect these forces during particle-bubble detachment measurement, since their contribution is minimal (Scheludko et al., 1976; Drzymala, 1994; Nguyen, 2003; Kowalczuk et al., 2011).

An ideal particle-bubble aggregate is shown in Fig. 1. At the moment of attachment, the capillary force (F_c) is the force responsible for particle-bubble interaction (Drzymala, 1994; Nguyen and Schulze, 2004), Fig. 1a. The resulting force forms an angle φ with the horizontal line drawn along the particle-bubble contact. The angle between the tangent to the bubble and tangent to the particle is the attachment angle θ also known as the contact angle, which determines the hydrophobicity of the surface (Drzymala, 1994).

At the moment of attachment, the vertical component of the capillary force which has been resolved from Fig. 1 is counterbalanced by other vertical forces such as the immersed weight (F_w) of the particle and the excessive force (F_e). During detachment (Pulling down) of the particle from the bubble as result of detachment forces (Pressure in the gas bubble, immersed weight of the particle and the turbulent acceleration) acting on the aggregate, the angle φ increases to a maximum of φ_o. This causes the capillary force to increase and reaches a maximum ($F_{c,max}$), Fig. 1b. Hence the angle of attachment θ reaches a critical value of detachment angle θ_d, any further increase in detachment force will break the particle-bubble aggregate Fig. 1b (Drzymala, 1994; Watanabe et al., 2011).

Detachment of particles in a flotation cell with mechanical pulp agitation is due to turbulence, generated by the motion of the rotor (Maksimov and Emeljanov, 1983). This creates liquid vortices, causing oscillatory motion of particles upon the bubble surface (Brożek and Młynarczykowska, 2010). According to Cheng and Holtham (1995), a particle-bubble aggregate under this motion behaves as a spring mass if the gas bubble is excited by external forces. When the particle-bubble aggregate is vibrated, the motion of the aggregate is considered to be simple harmonic, with a vibrational velocity. The details of the equation of motion of this particle-bubble aggregate have been reported (Holtham and Cheng, 1991; Xu et al., 2009). It was shown that the study of probability of detachment by means of a vibrational technique seemed to describe the typical conditions in the flotation cell.

Therefore, the vibrational velocity, acceleration and maximum vibrational force acting on the particle-bubble aggregate are given by Eqs. (3)–(5) respectively

$$V_{max} = \omega A = 2\pi f A \tag{3}$$

$$a_{max} = \omega^2 A = (2\pi f)^2 A \tag{4}$$

$$F_{v,max} = m(2\pi f)^2 A = \frac{\pi d_p^3}{6}\rho_p(2\pi f)^2 A \tag{5}$$

where ω is angular frequency, (rad/s), A is the amplitude (m), f is the oscillation frequency (Hz), m is the mass (kg), d_p is particle size (m) and ρ_p is the particle density (kg).

In this study, a modified vibrational apparatus similar to that of Cheng and Holtham (1995) for a fixed bubble and single particle was used for the detachment force measurement. The maximum

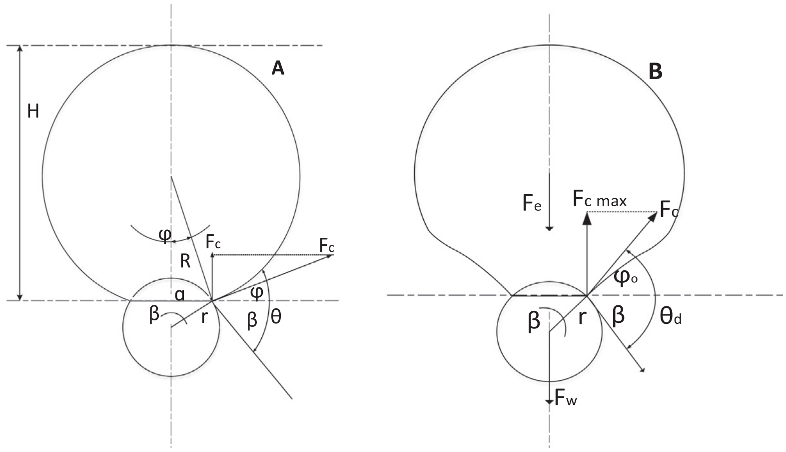

Fig. 1. Particle-bubble aggregate at the moment of particle attachment (A) and detachment (B) (Drzymala, 1994) (not to scale, r is the radius of the particle and R is the radius of the bubble).