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Mineral beneficiation by ionic microbubble in continuous plant prototype: Efficiency and its analysis by kinetic model

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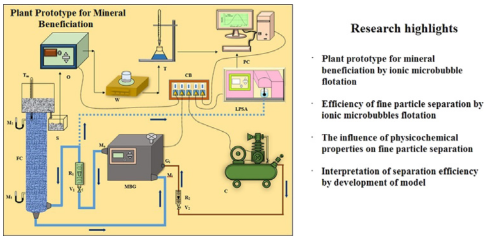
HIGHLIGHTS

- Plant prototype for mineral beneficiation by ionic microbubble flotation.
- Efficiency of fine particle separation by ionic microbubbles flotation.
- The influence of physicochemical properties on fine particle separation.
- Interpretation of separation efficiency by development of model.

GRAPHICAL ABSTRACT



Research highlights

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ABSTRACT

Microbubbles are miniature gas bubbles of less than 100 μm diameter in liquid. The performance of ionic microbubble for fine particle separation is investigated and reported in the paper. The effects of different operating variables and physicochemical properties of liquid on the separation characteristics of ionic microbubble are enunciated. A phenomenological kinetic model based on collision, attachment and detachment mechanisms of fine particle is developed to analyze the flotation characteristics of the ionic microbubbles. Generalized correlations for flotation rate constant and induction time are also developed based on the physicochemical properties of microbubble–particle mixture. It is concluded that ionic microbubble is highly efficient for removal of fine particles of opposite charge. The findings from this research may be helpful to understand and explain the process better and possibly can be used to modify and improve the microbubble aided flotation process.

1. Introduction

Separation of fine particles is widely encountered in mineral industries. A large sum of operating expenditures of mineral industries are associated with separation of mineral processes. Therefore the influence of separation process technology on the profitability is high in mineral industries (Rousseau, 1987). Flotation is most common means of separating the valuable components in this regard. Flotation is beneficial not only to mineral separation, a large variety of chemical species such as ions, molecules, microorganisms, oil droplets etc. are also separated by this method. They can either be separated from one another or concentrated from solution (Al-Shamrani et al., 2002; Gaudin et al., 1960; Matis and Mavros, 1991). The coarse particles are easily separated by the conventional flotation method but when the size of mineral particle is in micrometer range, it is very difficult to separate it. The poor recovery of fines mineral by flotation is mainly due to the low probability of bubble–particle collision, which decreases with decreasing particle size (Weber and Paddock, 1983). Conventional flotation are inefficient in encountering collision and attachment of fine particles and bubbles. For the recovery of fine mineral particles, the flotation cell should have fine bubbles or microbubbles suitable to catch these particles (Trahar and Warren, 1976). Microbubbles have been extensively used in the mineral

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and liquid effluent treatment, and especially for the flotation of particles having size less than 100 μm (Solari and Gochin, 1992). Microbubble due to their small size offers a large surface area. They experience a low degree of buoyant force, due to their small size, which gives them a long residence time in the liquid as compared to conventional bubbles (Parmar and Majumder, 2013). The charge on the surface of microbubble helps it, to become an propitious tool for the fine mineral separation (Han and Dockko, 1998). According to Jauregi et al. (1997) the potential applications of microbubbles can be grouped into four main zones: (1) flotation for the removal of biological and non-biological products; (2) protein recovery; (3) enhancement of oxygen mass transfer; and (4) bioremediation. Microbubble aided flotation has been widely employed in the various fields for the process intensification. They have been used for recovery of proteins (Amiri and Valsaraj, 2004; Jarudilokkul et al., 2004; Jauregi et al., 1997; Noble et al., 1998), recovery of microorganism (Hanotu et al., 2012), removal of heavy metal ions from water (Ciriello et al., 1982), removal of dye and pigment (Alves et al., 2006; Roy et al., 1992). Cilliers and Bradshaw (1996) used microbubble to recovery of fine pyrites. Shen and Wheelock (2000) reported that approximately 85% recovery of fine coal particles can be achieved by using microbubbles. The recovery of fines can be increased up to 95% using microbubbles with proper chemical agents (Han and Dockko, 1998). Separation can further be enhanced by using ultrasound with the microbubble (Shibata et al., 2008). Mechanical modification has also been done to improve this technology for mineral beneficiation (Yi-jun et al., 2009). Microbubble-aided flotation not only increases the recovery it also reduces the frother consumption (Ahmadi et al., 2014). The electrical double layer interactions and the particle and bubble charge can affect the rate of recovery for fine particles. The electrostatic interactions present between charged microbubble and particles of opposite charge may be a governing force for separation. Fuda and Jauregi (2006) carried out a detailed study to observe the mechanism of separation of proteins by ionic microbubbles. They concluded that electrostatic interactions were the driving force for the separation. Waters et al. (2008) also used ionic microbubble to separate fine binary mixture of mineral. They found that surface charge of microbubble can be changed by using surfactants. They compared the results obtained with conventional flotation method and observed that ionic microbubble has high recovery over conventional flotation. Recently, Johnson et al. (2009) reported that repulsive long-range interactions are responsible for the selective attachment of mineral particles to microbubbles in a charge-dependent manner. It is very clear that, the ionic microbubble has a potential to intensify recovery in mining industries. When considering the industrial applications of ionic microbubble in mineral separation, it is important to evaluate the benefits of ionic microbubble based on scientific principles, from an academic standpoint and to compare microbubble flotation technology with existing technology both in terms of its functional quality and effectiveness. Thus it becomes very necessary to examine the effect of physicochemical properties of liquid and mineral particle based on mechanism of ionic microbubble flotation. Therefore the present work is aimed to study the potential of ionic microbubble for the separation of binary fine particle by flotation. Furthermore, the effects of surfactants on the recovery of fine particle are also analyzed. This study may be helpful for the intensification of the flotation process in the application of mineral process and technology.

2. Experimental

2.1. Materials

In the present study three mineral particle mixtures such as (i) zinc oxide (ZnO) and silica (SiO_2) (ii) copper oxide (CuO) and silica (iii) aluminum oxide (Al_2O_3) and silica were used to study the separation characteristics of ionic microbubble. The surfactants cetyltrimethylammonium bromide (CTAB), sodium dodecyl sulfate (SDS) and Polysorbate 20 (Tween-20) were used to form ionic microbubble. The concentrations of CTAB and SDS were varied from 5 ppm to 35 ppm. The concentration of Tween-20 was varied from 0.015 ml/l to 0.18 ml/l. Preliminary tests carried out on the stability of ionic microbubble showed that 5 ppm of CTAB and SDS each was sufficient to ensure the dispersion without break down when being pumped (Parmar and Majumder, 2015), whereas in case of Tween-20, concentration 0.015 ml/l was sufficient to produce stable microbubble. All the chemicals used in the present work had a purity of $>98\%$ and were purchased from MERK Chemicals (India). The densities of the solution were measured with a specific gravity bottle. The surface tension was measured by tensiometer (model K9-MK1, Krüss GmbH, Hamburg, Germany). Previous studies reveals that microbubble suspension is a time-independent non-Newtonian pseudo-plastic fluid and its rheology is described by Ostwald–De Waele model or Power law model (Parmar and Majumder, 2014; Shen et al., 2008; Tseng et al., 2006)

$$\tau = K'\left(-\frac{dU_c}{dr}\right)^n \tag{1}$$

where K' and n are constants for a particular fluid. U_c is microbubble–particle mixture velocity and r is the radial distance. The constant K' is known as the consistency of the fluid and n is known as flow behavior index. The parameter n and K' are independent of geometry of the column (Larmignat et al., 2008). The values of n and K' are calculated experimentally in a horizontal pipe from the wall shear stress (τ) and the apparent shear rate (γ_a) as (Larmignat et al., 2008)

$$\tau = \alpha\gamma_a^n \tag{2}$$

The parameter α and the flow consistency index (K') of the microbubble–particle mixture are related as (Larmignat et al., 2008)

$$\alpha = K'\left(\frac{3n+1}{4n}\right)^n \tag{3}$$

The wall shear stress and apparent shear rate can be calculated from the volumetric flow rate of mixture (Q_m) and pressure drop (ΔP) in the pipe according to the following relations (Larmignat et al., 2008)

$$\tau = \frac{D_p \Delta P}{4L_p} \tag{4}$$

$$\gamma_a = \frac{32Q_m}{\pi D_p^3} \tag{5}$$

where D_p is diameter of pipe and L_p is length of pipe. The effective viscosity of microbubble–particle mixture (μ_e) in the flotation column is defined as the ratio of the shear stress at the wall to the average shear rate which was calculated by

$$\mu_e = K'\left(\frac{8U_c}{D_c}\right)^{n-1} \tag{6}$$

All the experiments in the present work were carried out at 25 ± 1 °C. The physical properties of liquid phase are listed in Table 1.