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Gas dispersion measurements in microbubble flotation systems

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ABSTRACT

This work summarises results of microbubble dispersion parameters in a controlled laboratory system. The effects of the temperature and frother concentration (MIBC) on the gas holdup (ε_g), superficial area flow density (S_b), superficial air velocity (J_g), bubble Sauter diameter (d_{32}) and air liberation efficiency were studied. The results obtained with natural water show that (a) increasing the temperature from 10 to 30 °C significantly increased the bubble Sauter diameter from 80 to 150 μm, improving the air liberation (bubble formation) and (b) increasing the superficial air velocity from 0.01 to 0.06 cm/s enhanced the air holdup from 0.4% to 1.8%, the Sauter diameter from 60 to 120 μm and the bubble surface area flux from 5 to 25 s^{-1}. The experimental results also showed that frother addition (MIBC) reduced the Sauter diameter, while increasing all other variables.

1. Introduction

In the last few decades, the use of microbubbles that are generated by depressurisation of dissolved air in water (DAF) has attracted interest due to its possible applications. In particular, in the mineral and liquid effluents treatments, and especially for the flotation of fine particle sizes (Rubio et al., 2002, 2003; Capponi et al., 2005).

For efficient mineral flotation recovery of coarse and fine particles, there must be an optimal bubble size and bubble size distribution whereby the number of particles "captured" by bubbles reaches a maximum (Yoon 1993, 2000; Rubio et al., 2006). For the recovery of small particles, the flotation cell should have fine bubbles or microbubbles suitable to catch these particles (Yoon, 2000; Rubio et al., 2003; Zhou et al., 1997). Unfortunately, this does not occur in practice and the flotation cells that are commercially available do not provide the required bubble size distribution.

According to some authors (Capponi et al., 2005), using microbubbles (an injection of 30–100 μm) in addition to conventional bubbles (between 600 and 2500 μm) for the flotation of fine particles (Cu and Mo sulphides) led to slight improvements in recovery (2%) and in flotation kinetics (rate constant, 3% higher) on the laboratory scale. It was claimed that by decreasing the bubble size distribution, the bubble surface area flux and the fine particle capture were both increased. However, the use of "single" microbubbles (without coarse bubbles) in ore flotation (fine and coarse particles) has proven unsuccessful. This has been attributed to problems with the low lifting power of these bubbles, especially at high solid concentrations (Solari and Gochin, 1992; Peng et al., 2005; Capponi et al., 2005).

Conversely, the use of flotation is showing great potential in effluent treatment due to the high throughput of modern equipment, low sludge generation and the high efficiency of the separation schemes already available. Examples can be found in the treatment of contaminated water (oils, pigments, heavy metals removal), in the recovery of proteins, sugar impurities, inks and resins, as well as in microorganism separation and the treatment of sewage and sludge, turbidity, colour, suspended solids, and micro-organisms (Rubio et al., 2002; Englert et al., 2009; Carissimi et al., 2007).

2. Background

The micro-bubble generation equipment is well described in several papers (Rodrigues and Rubio, 2003), so only a brief summary will be described in this section. An important step in micro-bubble formation is air dissolution. The air dissolution process obeys Henry's law, where the kinetics are mass transfer dependent and highly influenced by the pressure and design of the saturator (3–6 atm). During the generation of the bubbles, the energy transferred is determined by the superficial tension and the pressure gradient around the constriction valve (Rodrigues and Rubio, 2003).

Bubbles are formed by a reduction in pressure of water that has been pre-saturated with air and occurs at pressures higher than atmospheric. The supersaturated water is forced through needle valves or special orifices and clouds of bubbles 0.02–0.1 mm in diameter are produced just down-stream of this constriction.

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A disadvantage of the DAF process is the high cost of water saturation required for bubble formation. However, it has been shown that bubble generation is possible at working pressures lower than 3 atm by lowering the air/liquid surface tension in the saturator. It was concluded that very low concentrations of surfactants or flotation collectors are required to operate the DAF units at 2–2.5 atm (Féris et al., 2001). This process can drastically reduce the cost of energy and optimisation of the whole process (Féris and Rubio, 1999; Féris et al., 2001).

These results were explained as cavity formation occurring as a result of a minimum energy, ΔF (joules), being transferred to the liquid phase and forming bubbles, following the equation (Takahashi et al., 1979):

$$\Delta F = \frac{\frac{16}{3}\pi \cdot \gamma^3}{(P_0 - P_a)^3} \quad (1)$$

where γ is the air/water surface tension (Nm^{-1}), P_a is atmospheric pressure (atm or Pascal units), and P_0 is the saturation pressure (atm or Pascal units).

Thus, less energy is required to generate micro-bubbles with a lower air/liquid interfacial tension, or with greater pressure differences between the liquid phase and atmosphere. Accordingly, in reducing γ, the liquid/solid attrition will be reduced and the flow fluid velocity and the bubble formation will become faster.

Under light turbulent conditions, Libra (1993) observed that oxygen dissolution in water decreases with anionic surfactants. This effect is reduced in turbulent conditions when the bubble surface area generation increases after improvement of mass transfer.

Another effect of the surfactant is the diminution of coalescence and the increase in the superficial area. However, not all surfactants prevent coalescence. An example is the use of non-ionic surfactants (commonly used as deformers), which are used to avoid bubble surface area generation (Zlokarnik, 1979).

The nucleation of air may be homogeneous or heterogeneous. In the case of homogeneous nucleation, the air nucleation around the molecular cavities precedes micro-bubble formation, and may be favoured by the presence of high concentrations of gas close to this cavity. Commonly, heterogeneous nucleation is present on the surface of the constrictor because the surface of the needle valve serves as a site for air nucleation. Additionally, the presence of particles favours air nucleation.

In the last decade, the froth flotation industry has used a variety of sensors to evaluate the aeration quality of their processes. Conventional bubble sizes are used (500–2500 m). Several prototypes of sensors and techniques have been developed for evaluating the bubble diameter in conventional flotation cells; although the most commonly used methods involve image analysis. However, measuring the Sauter diameter of a micro-bubble dispersion has it owns difficulties and requires special equipment.

Rodrigues and Rubio (2003) developed a device for measuring the bubble diameter of micro-bubbles in a two-phase system. Their system included a bubble capture cell, a microscope and a digital camera. One of the more important details of this system is that turbulent movements must be avoided, as they make it difficult to obtain a clear picture.

Gas holdup is the volume percentage or volume fraction of air within the collection zone. Ahmed and Johnson (1989) found that gas holdup favours flotation kinetics because it increases the number of bubbles, and therefore the superficial area available for particle collection. Frequently, this variable is estimated using a simplified mathematical model of Maxwell (Eq. (2)), which requires the measurement of the electrical conductivities of the pulp (k_{ls}, liquid–solid dispersion) and the dispersed phase (k_{lsg}, liquid–gas–solid). Tavera et al. (1995) developed an industrial air holdup sensor, which has been used in off-line industrial measurements.

$$\varepsilon_g = \frac{1 - k_{lsg}/k_{ls}}{1 + 0.5 \cdot k_{lsg}/k_{ls}} \quad (2)$$

The rate of bubble surface area passing through a cross section of the flotation cell is also known as the bubble surface area flux (Gorain et al., 1997). The importance of this variable is its relationship to the flotation efficiency. It can be estimated from the Sauter diameter and the superficial gas velocity, as:

$$S_b = \frac{6 \cdot J_g}{d_{32}} \quad (3)$$

To evaluate the aeration state in conventional flotation cells, Gomez and Finch (2007) proposed a gas velocity sensor, which was constructed with a plastic tube large enough to be introduced in the collection zone and to reduce the bubble sampling biases. The authors explained that the collected bubbles reach the liquid surface in the tube and burst. If the tube is closed, the pressure increases; this pressure is registered by a data acquisition system and serves to compute the superficial air velocity (J_g). Thus, the air flow (Q_g) is commonly estimated measuring J_g and multiplying by the cross-sectional area of the flotation cell (A).

$$Q_g = J_g \cdot A \quad (4)$$

Matiolo et al. (2011) have characterised the aeration variables (J_g, S_b, d_{32} and ε_g) with fine bubble sizes (470–1000 m) in a water/air system. The gas holdup and bubble size (and their distributions) were found to be strongly dependent on the concentration of Dowfroth 250 and the superficial gas velocity. A fairly linear relationship between the experimental ε_g and the bubble superficial area flux (S_b) was established, the results of which were compared to those calculated using drift flux analysis. No similar studies appear to be reported with micro-bubble size dispersions, (10–100 m) and accordingly, the main goal of this work is to contribute to the knowledge of this subject.

3. Experimental

The experimental setup was composed of two principal parts: the air-saturation water reactor and the flotation column. The saturation reactor was made of polyvinyl chloride (PVC, 80; 30 cm internal diameter; 140 cm high). This reactor was designed for saturated-water level control and internal pressure control; the internal pressure was kept constant at 54 psig (±0.2). To visualise the bubble dispersion, the flotation column was made with a

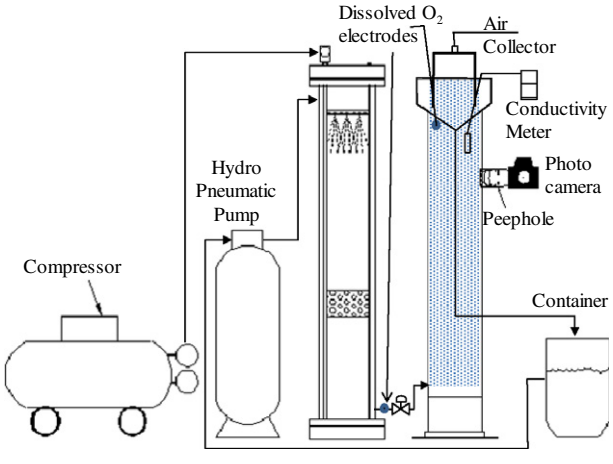

Fig. 1. Experimental setup.