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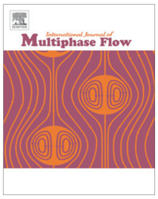

Attachment of solid elongated particles on the surface of a stationary gas bubble

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ABSTRACT

Froth flotation is a separation process which plays a major role in the mining industry. It is essentially employed to recover a vast array of different valuable commodities such as rare earth minerals essential to the manufacture of high-tech products. Owing to its simplicity, the process is also widely used for the de-inking of recycled paper fibres and for the removal of pollutants from waste water. The flotation process essentially relies on the attachment of solid particles on the surface of gas bubbles immersed in water. The present study seeks to investigate the effect of the particle shape on the attachment mechanism. Using an in-house optical micro-bubble sensor the approach, the sliding and the adhesion of micron milled glass fibres on the surface of a stationary air bubble immersed in stagnant water is thoroughly investigated. The translational and rotational velocities were measured for fibres of various aspect ratios. The results are compared with a theoretical model and with experimental data obtained with spherical glass beads. It is found that the fibre orientation during the sliding motion largely depends on the collision area. Upon collision near the upstream pole of the gas bubble the major axis of the fibre aligns with the local bubble surface (tangential fibre alignment). If collision occurs at least 30° further downstream only head of the fibre is in contact with the gas–liquid interface (radial fibre alignment).

Introduction

Motivation

Froth flotation is a versatile separation process which plays a major role in the mining industry. It is essentially employed to recover a vast array of different valuable commodities such as copper, zinc, nickel, phosphate and rare earth minerals essential to the manufacture of high-tech products (Fuerstenau et al., 2007). Owing to its simplicity, the process has more recently seen widespread applications in the non-mining field. Flotation is for instance used for the de-inking of recycled paper fibres (Kemper, 1999) and for the removal of pollutants from waste water (Rubio et al., 2002). In mineral froth flotation the separation can be accomplished in a flotation cell, which is essentially a tank fitted with an impeller (Ahmed and Jameson, 1985). The impeller disperses air into fine gas bubbles and agitates the slurry. It provides a favourable environment in the cell for the promotion of bubble collision with the finely ground ore (Fuerstenau et al., 2007). Typical values of particle diameters, for which the recovery rate is high, vary from approximately $d_p = 10\ \mu m$ to $d_p = 150\ \mu m$. (Tao, 2005; Jameson, 2010). Many ore minerals are naturally hydrophilic. The addition of so-called "collectors" to the slurry, which are absorbed by the mineral surface, renders the precious mineral particles hydrophobic (Rosenqvist, 2004). The hydrophobised particles then attach to the surface of the rising bubbles, whose size generally ranges from $d_b = 0.6$ to 2 mm in diameter (Rubio et al., 2002). The particle-bubble aggregates are conveyed to the top of the flotation cell to form a rich mineral-laden froth layer, which eventually overflows into a launder as a separate product. Since pure liquids generally do not foam, "frothers" are utilised to control the bubble size and to stabilise the froth (Cho and Laskowski, 2002). The gangue, i.e. the commercially valueless hydrophilic material, eventually exits the flotation cell as slurry.

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Particle shape

Ore grinding in froth flotation is an important step to liberate the valuable mineral particles from the gangue (Forssberg et al., 1993). Kursun and Ulusoy (2006) showed for instance that the shape of talc mineral particles produced by milling considerably deviated from an ideal sphere. Talc minerals ground by rod milling showed higher elongation and flatness than those ground by ball milling. The study of Rahimi et al. (2012) also suggested that rod milling caused an elongation of the particles and that ball milling caused a greater particle roundness. Various studies have shown that the particle elongation increases the recovery rate. Koh et al. (2009) found that ground ballotini particles had a higher recovery rate than spherical ballotini particles. The work of Yekeler et al. (2004) also corroborated this finding. The team experimentally observed that particle elongation increased the ease, with which a particle attaches to a bubbles surface. Particle roundness tended to have an adverse effect on the recovery rate. Note, that the recovery rate k is the rate at which the desired particles are recovered from the suspension. In a flotation tank, the number concentration $c(t)$ of the desired particles will decay exponentially with time. Ahmed and Jameson (1985) suggested the following formula $c(t) = c_0 \exp(-kt)$, where c_0 was the initial concentration in the tank.

Particle attachment on bubble surface

The attachment of a solid particle on the surface of a gas bubble can be divided into three successive stages: the particle approach, the collision with the bubble and the sliding down the gas–bubble interface (Schulze, 1989; Albijanic et al., 2010). The downward sliding motion of the particle is caused by the gravity and also by the hydrodynamic forces arising from the local water flow around the rising bubble. Should the particle approach the bubble surface within the range of attractive surface forces, a thin intervening liquid film between the gas–liquid interface and the solid–liquid interface forms. The liquid film eventually drains, leading to a critical thickness at which rupture occurs (Ralston et al., 1999). The rupture of the liquid film results in the formation of a stable three-phase contact (Schulze, 1992). The deployment of high speed camera systems has been favoured in recent years to observe the particle attachment in great detail. Wang et al. (2003a) photographically recorded the attachment of free falling spherical glass beads on a stationary air bubble, which had undergone various surface treatments. Gu et al. (2004) investigated the attachment of rising spherical hydrogen bubbles on a larger fixed bitumen particle. Hubička et al. (2013) measured the trajectories of an approaching large solid spherical particle on a stationary gas bubble. The sliding was however left out by the authors. Verrelli et al. (2014) were the first to look at the attachment of non-spherical particles. They measured the induction time, i.e. the time required for the liquid film to thin to its critical film thickness (Ye et al., 1989), of ‘angular frit’ particles falling on a gas bubble. The above state of the art clearly shows that the attachment process has largely been limited to the attachment of perfectly spherical particles. The effect of shape irregularity on the attachment process has received scarce attention. To date only one attempt can be found in the literature. The present piece of work aims to alleviate this shortcoming by experimentally investigating the attachment of elongated particles with an aspect ratio of up to 7.

Methods

Experimental facility

The experimental procedure employed to visualise attachment of solid particles was inspired by the work of Verrelli et al. (2014). As illustrated in Fig. 1 the experimental set-up essentially consisted of water tank in which a needle was placed in a horizontal position. The 25 gauge ultra-smooth hydrophobic needle with a ta-C diamond-like carbon coating (SGE Analytical Science, Diamond MS Syringe 0355321) was attached to a 50 μl precision syringe (Hamilton, 1805RNSYR). It allowed blowing a stable and stationary air bubble, whose diameter could be varied from $d_b = 1.3$ mm to $d_b = 1.7$ mm. A larger bubble diameter resulted in a detachment of the gas bubble from the needle. The adhesion force holding the bubble on the needle tip could no longer overcome the buoyancy force. The present bubble size range matched the typical size range frequently found in the literature (Huang et al., 2011). The water was kept at a constant room temperature of 20 °C and had a pH value of 7.8. The opened-water tank was made of transparent Plexiglas walls. A tube fastened in a vertical position had its immersed extremity placed 15 mm away from the bubble upper pole (henceforth referred to as the upstream pole), which corresponded to a distance of about 10 bubble diameters. The reason behind the use of the fastened vertical tube was threefold: 1. to guide the particles all the way down to the gas bubble, 2. to avoid an interference of the falling particle with the surrounding liquid and 3. to hold the Pasteur pipette in a stable vertical position. The Pasteur pipette, containing the particles heavily diluted in water, could then be placed in the tube in question. The bulb of the pipette in contact with ambient air was pierced to avoid a squeezing that would potentially give the particles an undesired acceleration. By releasing the finger from the bulb the solid particles could start their decent with an initial velocity close to zero. The present facility unfortunately did not exactly reproduce all mechanisms observed in an industrial flotation cell. The motion of the liquid and of the gas phases were here left out, and so were the effect of frother and collector addition. To the best of the authors’ knowledge the present study, even though it is a fairly simple system, is the first of its kind that seeks to investigate the effect of particle elongation on the overall attachment mechanism, which is of chief importance in the flotation process. It is hoped that the present results will help build more complex models in the future.

Solid particles

Experimental tests were performed with spherical particles for comparison purposes and fibre-like elongated particles. The glass spherical particles (Wiwox, STGP002) had a particle-to-liquid density ratio of $S = \rho_S/\rho_L = 2.45$ and a diameter ranging from $d_p = 50$ μm to $d_p = 100$ μm. The milled glass fibres (3B-Fibreglass, MF01ER) had a particle-to-liquid density ratio of $S = 2.5$ and a length ranging from 100 μm to 200 μm in the long-axis direction (major axis). Detailed images of the elongated particles obtained

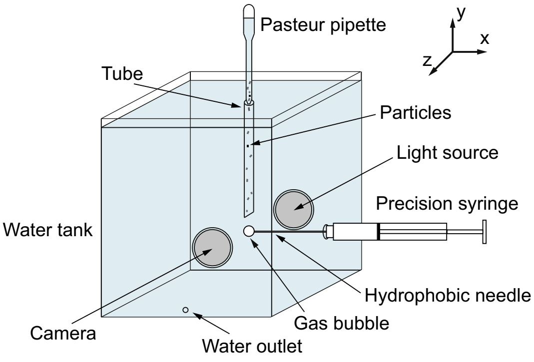

Fig. 1. Schematic of the test facility.