

Collision processes involving a single rising bubble and a larger stationary spherical particle

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ABSTRACT

The adhesion of bubbles to a particle surface is a ubiquitous natural phenomenon that plays a critical role in numerous industrial processes. The aim of this work is to broaden the knowledge of the hydrodynamic interactions that occur between bubbles and solids of a comparable size. Focusing on collision processes between a single rising bubble with an immobile surface ($D_b < 1$ mm) and a larger stationary solid spherical particle, the bubble trajectory, collision efficiency and maximum collision angle were determined experimentally. All existing theoretical models of mineral flotation are based on the fundamental assumption that liquid flow around the bubble is both fore-and-after asymmetric in a vertical orientation and left-and-right symmetric in a horizontal orientation. However, when a small bubble collides with a larger spherical particle, the liquid flow around the bubble is asymmetric in all directions. Consequently the existing theoretical models enabling the estimation of the collision efficiency or maximum collision angle were tested for description of collision processes between bubbles and solids of a comparable size.

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1. Introduction

The formation of bubble–particle aggregates, caused by bubble–particle interaction, is a fundamental process occurring in many industrial applications. Flotation is one of the most important examples of such a process. Originally developed in the mining industry to recover valuable minerals from mined ores, flotation employs air bubbles as carriers to recover hydrophobic entities from complex slurries. Due to its high separation efficiency, cost effectiveness and simplicity of operation and maintenance, flotation has been extended to other industries utilising solid–solid and solid–liquid separation processes. Such processes include: bitumen recovery from oil sands; the de-inking of recycled paper pulp; de-oiling in heavy oil exploration; the removal of fine solids in industrial and domestic water treatment; the treatment of multiphase toxic effluents in the chemical and mining industries; and, plastics separation and recycling. The use of flotation in plastics separation has grown in line with the need to recycle plastics (e.g. Shent et al., 1999; Dodbiba and Fujita, 2004). However, most previous studies have been based on the needs of mineral flotation, and, consequently, have focused on particles that were much smaller than the bubbles. There is a fundamental difference in the interaction between plastics particles and bubbles in plastic flotation. The size of the plastic particles is measured in millimetres and, thus, the floating

aggregate is usually formed by one particle and a number of adhered bubbles. In mineral flotation the floating aggregate is usually formed by one bubble and a number of adhered particles. Our work contributes to a better understanding of the bubble–particle interaction process when the particle is larger than the bubble. A stationary spherical particle was chosen as a model particle imitating plastic material. We focussed only on the collision process between this stationary particle and one raising bubble; here bubble and particle sizes play the most important role in all calculations. A methodological description of such collision process is followed by experimental results, which are then compared with those obtained by theoretical models of mineral flotation.

2. Bubble–particle interaction theory

An identical mechanism of bubble–particle interaction can be assumed for both types of flotation (mineral flotation with $D_p/D_b < 1$; plastics flotation with $D_p/D_b > 1$; here D_p and D_b are the particle and bubble diameters, resp.). For efficient bubble–particle capture, a sufficiently close encounter is required. The process is initially controlled by the hydrodynamics governing bubble–particle approach in the liquid phase. As the particle and bubble come closer, the influence of intermolecular and interfacial forces increases. The liquid film between the bubble and particle surfaces begins to drain away, causing the film to rupture. The three-phase (air–water–particle) contact line becomes larger until a stable wetting perimeter is established, and, at this point, a stable bubble–particle aggregate is formed. This bubble–particle interaction process is usually described as consisting of a sequence of three discrete steps (Derjaguin and Dukhin, 1960; Nguyen et al., 1997; Ralston et al., 1999;

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Ralston et al., 2002; Nguyen and Schulze, 2004): (i) collision – approach of the bubble and the particle to the contact distance; (ii) attachment – adhesion of the particle to the bubble surface when the particle is smaller than the bubble, or adhesion of the bubble to the particle surface when the bubble is smaller than the particle. The attachment process begins with the drainage and rupture of the liquid film, and continues with contact line movement; (iii) stability – detachment of the bubble from the particle surface occurs when the bubble–particle aggregate is unstable.

In mineral flotation, particle motion around a rising bubble is commonly considered as motion around a spherical body with rotational symmetry in the gravitational direction. To describe liquid flow around an air bubble it is convenient to choose an axisymmetrical (polar spherical) coordinate system and a three-dimensional (3D) analysis of bubble–particle interaction is often simplified into a two-dimensional (2D) analysis. The liquid flow around bubbles typically used in flotation is fore-and-aft asymmetric (Nguyen, 1999), and strongly affects the encounter and attachment mechanisms. Due to the asymmetry of liquid flow, small particles can be pushed away from the bubble surface despite the fact that the distance of such particles from the bubble vertical axis is less than the bubble radius. The critical trajectory, known as the grazing trajectory, distinguishes the trajectories of particles that encounter the bubble from the trajectories of those that do not, and is characterized by the critical radius R_c and the critical collision angle $\varphi_{c,max}$. Here, the polar angle φ is measured at the bubble centre and from the front stagnation bubble point. The typical scheme of bubble–particle interaction in mineral flotation is illustrated in Fig. 1A. Bubble–particle interaction in plastics flotation, in which the particle is larger than the bubble, is described in Fig. 1B. The bubble grazing trajectory (grazing radius R_c) restricts the collision area within which a bubble collides with a particle. Here, the polar angle φ is measured at the particle centre and from the particle vertical bottom half-axis.

2.1. Bubble motion in an aqueous solution of a surface-active agent

The hydrodynamic field around a moving bubble in stagnant liquid can be described using the Navier–Stokes equations (e.g. Nguyen, 1999), any solution of which must satisfy all boundary conditions at the bubble surface. A general analytical solution does not exist, but it is possible to solve these equations in two extreme cases: for small bubbles ($Re < 1$, Stokes conditions); for large bubbles ($Re \gg 1$, potential conditions). The Reynolds number (Re) is defined as

$$Re = \rho_l U_b D_b / \eta_l \tag{1}$$

Here, ρ_l and η_l are the liquid density and dynamic viscosity; D_b and U_b are the bubble diameter and bubble rise velocity, respectively. At small Reynolds numbers, the bubble rise velocity is given by the Stokes equation:

$$U_{b,Stokes} = \frac{2R_b^2 g (\rho_l - \rho_b)}{9\eta_l} \tag{2}$$

Here the bubble has an immobile surface and its velocity is the same as that of a solid sphere. The drag coefficient C_D is well correlated to the Reynolds number (Clift et al., 1978; Michaelides, 2006) by the function:

$$C_D = 24 / Re. \tag{3}$$

For bubbles with a diameter of more than 0.2 mm, the properties of the liquid medium play an important role. Since the mechanism was first described by Frumkin and Levich (1947) and Levich (1962), the impact of surfactants on velocity reduction has been well documented (Clift et al., 1978; Dukhin et al., 1998; Michaelides, 2006; Nguyen and Schulze, 2004). The motion of bubbles in a liquid is influenced by the kinetics of surfactant

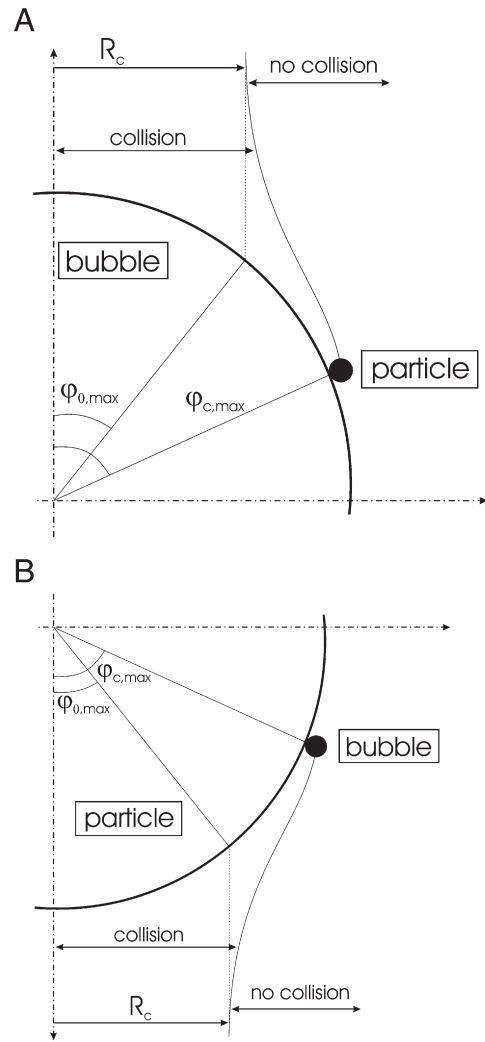


Fig. 1. Scheme of bubble–particle interaction process. A – single rising bubble and small falling particle; B – small rising bubble and large stationary particle. Grazing trajectory with radius R_c , maximum initial angle $\varphi_{0,max}$ and maximum collision angle $\varphi_{c,max}$ are denoted.

transport. The surfactant concentration varies along the surface of a bubble, reaching its maximum level at the rear stagnation point and its minimum level at the front stagnation point. During bubble rise in a surfactant solution, surface contamination often creates an immobile cap on the rear surface around the stagnation point, while the front part of the bubble surface remains mobile. When this happens the front part of the bubble becomes stretched, and the rear part becomes compressed. Due to the gradient of the surfactant concentration, a gradient exists along the bubble surface at the interface between the bubble and liquid. This gradient retards the surface of the bubble, and strongly affects the local stress balance at the bubble–liquid interface. Therefore, the drag on a bubble in a surfactant solution is less than that on a solid particle, but greater than that on a bubble in pure water. As the use of non-linear Navier–Stokes equations makes it very difficult to achieve an analytical solution in the case of intermediate Reynolds numbers, empirical models are often used to predict bubble rise velocity.

Nguyen and Schulze (2004) recommended two types of semi-empirical equations, depending on the value of the Reynolds number. For small bubbles in contaminated water, the bubble shape is spherical and the drag coefficient corresponds to that of solid particles. The bubble terminal velocity U_b thus given is:

$$U_b = U_{b,Stokes} / \left\{ 1 + \frac{Ar / 96}{(1 + 0.079Ar)^{0.755}} \right\} \tag{4}$$

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