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Detachment of particles from bubbles in an agitated vessel

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ABSTRACT

The flotation process is widely used to separate valuable minerals from waste in the minerals industry. It is well known that recovery decreases with increasing particle size, and a reason often given is that large particles detach from bubbles in the turbulent shear flow induced by the impeller in mechanical flotation cells. The energy produced by the impeller is transferred to the liquid in the cell and dissipates throughout the tank. In the impeller region, the turbulence is non-isotropic, but in a very short distance, it becomes isotropic, with the typical cascade of eddies from large to micro-scale length scales.

The aim of this study is to observe the behavior of particle–laden bubbles in the turbulent shear flow near a rotating impeller in a flotation cell. An agitated vessel was constructed in which bubbles could be introduced beneath the impeller. Bubbles were generated in a liquid-fluidized bed in a special chamber beneath the cell, in which the fluidizing liquid contained a collector that enabled the particles in the bed to adhere to the bubbles. When the bubbles entered the impeller zone, some particles were observed to detach, while others remained attached to the bubble and rose out of the vessel as a flotation product. The fractional detachment of particles was related to the mechanical energy dissipation rate in the region of the impeller. A standard Rushton turbine was used. The results are compared with theoretical predictions of Schulze (1977, 1982).

1. Introduction

Flotation is used to separate valuable mineral particles from gangue material, and also in wastepaper recycling for separating ink particles, and for removal of blue-green algae from waste waters. For the flotation of mineral particles, mechanical cells are widely used. To suspend the particles in the cell a rotor and a stator are provided. At typical impeller rotational speeds, the Reynolds number is quite high and the flow is fully turbulent. Except for the small region quite close to the impeller, the turbulent flow is isotropic and can be described by the theory of Kolmogorov (1941). A range of eddies of different sizes is produced, and energy cascades from eddies of large dimension, the production range, through to smaller eddies known as the inertial sub-range, down to micro-scale eddies. It is in the latter eddies that the mechanical energy is dissipated into heat by the action of viscosity.

Particle size is an important flotation variable, and it is known that the rate constant for ultrafine and coarse particles is lower than for intermediate particles. In this context, ultrafine mineral particles are those less than 20 μm and coarse particles are above 100 μm, both figures being convenient approximations. The influence of particle size on rate of recovery of minerals from flotation pulps has been investigated by several researchers (Jameson et al., 1977; Jowett, 1980; Trahar, 1981; Ahmed and Jameson, 1985; Yoon and Luttrell, 1989). Schulze (1977, 1982) in particular developed a theory in which it is hypothesized that detachment may occur when a bubble is trapped in the center of a rotating eddy in the turbulent flow, and a particle on the surface experiences a centrifugal force as a result. If the centrifugal force exceeds the surface tension forces that tend to keep the particle attached to the bubble, the particle detaches. Schulze proposed a critical dimensionless group, the Bond number *Bo*, which is the ratio of the centrifugal force of detachment to the capillary retaining force, and detachment occurs when $Bo > 1$.

In the present work, Schulze's hypothesis and the criterion for detachment is tested, by measuring the detachment of particles from bubbles in a well-characterized flow field developed by a Rushton turbine in a suitably-designed flotation cell. The fractional detachment of particles from bubbles is represented in terms of the Bond number. Silica and glass particles with a range of sizes were used as test materials.

2. Theoretical background

In mechanical flotation cells, the flow field generated by the impeller is turbulent and the local rate of dissipation of mechanical energy through eddy formation is high. The theory developed by Schulze (1977, 1982) is based on the hypothesis that when a bubble–particle aggregate finds itself in the eye of a rotating eddy in the

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region of the impeller, the particle experiences a centrifugal force that may overcome the surface tension force that is holding the particle at the interface. The particle will then detach.

The forces acting on a particle may be calculated with reference to Fig. 1, in which r_p is the particle radius, r_0 is the distance of the three-phase contact line from the vertical axis; h is the immersion depth of the particle; H is the height of the spherical cap above the meniscus; z_0 is the height of the meniscus above the three-phase line (deformation of the liquid meniscus at the solid surface), θ is the particle contact angle, ϕ is the polar angle, i.e., the angle between the surface tension direction (the tangent of the meniscus at the three-phase contact line) and the horizontal, and ω is the angle subtended by the vertical axis and the position of the three-phase contact line.

We now calculate the components of the forces acting on the particle (Nutt, 1960; Princen, 1969; Schulze and Stoeckelhuber, 2005). Note that for the time being we will calculate the forces as if the system were static, extending the analysis to the dynamic case later. The force of gravity acting on the particle is given by:

$$F_b = (4/3)\pi r_p^3 \rho_p g, \tag{1}$$

where r_p and ρ_p are the particle radius and density; g is the gravitational acceleration, which is directed vertically downwards, and x is the unit vector in the direction of interest.

The up-thrust applied by the liquid on that part of the bubble volume immersed in the liquid is given by:

$$F_b = (\pi/3) r_p^3 \rho_l g (1 - \cos\omega)^2 (2 + \cos\omega), \tag{2}$$

where ρ_l is the liquid density.

The force due to the hydrostatic pressure of the liquid of height z_0 above the contact area is expressed as:

$$F_{hyd} = \pi r_0^2 \rho_l g z_0 = \pi r_p^2 \rho_l g z_0 \sin^2\omega, \tag{3}$$

but Schulze (1984) showed that this term is negligible in flotation when the particle size is <300 μm and the contact angle is <90°.

The capillary force stabilises the attachment of particles to the gas–liquid interface. It acts along the tangent to the gas–liquid interface at the three-phase contact line and tends to pull the particle into the gas phase. The equation for the force in the vertical direction is

$$F_{ca} = 2\pi r_p \sigma \sin\omega \sin(\omega + \theta) \tag{4}$$

where σ is the surface tension of the liquid.

Under the action of surface tension, the pressure inside the bubble is greater than that in the liquid outside the bubble, by the amount $2\sigma/r_b$, from the Young–Laplace equation. Since part of the solid particle is exposed to the gas in the bubble, there will be a force tending to push the particle away from the bubble. With a small correction (Schulze, 1984), this force may be written

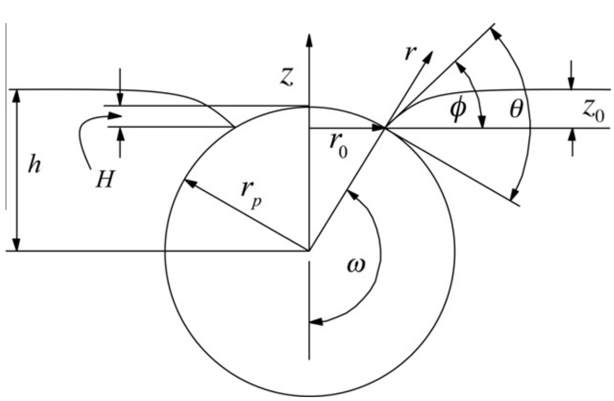

Fig. 1. Coordinate system for a spherical particle located at the gas–liquid interface.

$$F_\sigma = \pi r_p^2 \left(\frac{2\sigma}{r_b} - 2 r_b \rho_l g\right) \sin^2\omega. \tag{5}$$

The detaching force due to the rotation of the particle about the center of the bubble, with acceleration b_m:

$$F_d = (4/3)\pi r_p^3 \rho_p b_m \tag{6}$$

In the presence of the turbulence induced by the impeller in the flotation cell, an external centrifugal force acts on a particle on the surface of a rotating bubble. The acceleration provided to the aggregate was denoted the 'machine acceleration' by Schulze (1982), who showed that it could be related to the rate of energy dissipation in the cell by:

$$b_m = 1.9\varepsilon^{2/3}/D_b^{1/3}, \tag{7}$$

A dimensionless Bond number Bo can be defined as the ratio of forces of detachment to those of attachment. Thus

$$Bo = \frac{F_g - F_b + F_d + F_\sigma}{F_{ca}} \tag{8}$$

Substitution of the forces gives, with $D_p = 2r_p$,

$$Bo = \frac{D_p^2(\Delta\rho g + 1.9\rho_p \varepsilon^{2/3}/D_b^{1/3}) + (3/2)D_p((4\sigma/D_b) - D_b \rho_l g)\sin^2\omega}{6\sigma \sin\omega \sin(\omega + \theta)} \tag{9}$$

where D_p is the particle diameter. In a system where the contact line can move freely around the surface of the spherical particle, and is not pinned at any place, Schulze (1977) showed that the maximum attachment force occurs when

$$\omega = \pi - \theta/2 \tag{10}$$

Eq. (9) is Schulze's expression for the Bond number, with the factor 1.9 arising from his original investigation. We have reconsidered the theoretical path taken by Schulze, and have found a number of errors in the derivation. Accordingly, we arrived at a slightly different result, that we designate the *modified* Bond number.

2.1. Modified Bond number

There are several points at which Schulze's analysis is questionable; these relate to

(a) the appropriate radius of the eddy;
(b) the omission of the buoyancy force;
(c) a missing factor of 1.5.

2.1.1. The appropriate radius of the eddy

The forces considered in the Bond number are the capillary forces acting at the gas–liquid interface, and the centrifugal force induced by the vortex motion, in the isotropic turbulent flow generated by the impeller. The centrifugal force is simply the product of the mass of the particle and the centrifugal acceleration u^2/r, u being the tangential velocity and r the radius of rotation, equal to the radius of the bubble. To find the force, we need to know the tangential velocity. Schulze (1977) did not provide the details on this point, relying on the work of Liepe (1977).

The energy and the velocity components of eddies in the inertial subrange are drawn from the Kolmogorov theory of isotropic turbulence in which the energy spectrum is expressed as:

$$E(k) = C_1 \varepsilon^{2/3} k^{-5/3} \tag{11}$$

where C_1 is a universal constant whose value is 1.5 (Pope, 2000). Eq. (10) is the '5/3 power law' of Kolmogorov. The mean velocity fluctuations in the inertial sub-range are given by