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The dynamic contact angle of a bubble with an immersed-in-water particle and its implications for bubble–particle detachment

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ABSTRACT

The contact angle is of great importance in measuring the wetting characteristics of mineral particles. The dynamic contact angle is more relevant to flotation than the static contact angle, as the flotation environment is generally in a turbulent regime. Therefore, the dynamic contact angle should be used in the calculation of the capillary force which stabilizes bubble–particle aggregates in a turbulent field. In this paper, the static contact angle and the dynamic contact angle of a bubble detaching from a 3 mm stainless steel particle were measured using a high speed camera. The static contact angle calculated from the force balance analysis on the bubble was consistent with the angles measured optically (71.3°), which is in line with the published value (72°). Using the sphere tensiometry method, the advancing and receding contact angles were measured to be 106° and 45°, respectively. The detachment process was captured using a high speed camera operated at 1000 frames per second. The three phase contact on the left side of the bubble retracted as the contact angle in the upstream reached the advancing contact angle. However, the three phase contact on the right side of the bubble pinned on the surface of the particle as the contact angle in the downstream did not reach the receding contact angle. The dynamic contact angle of a bubble detaching from a particle was measured and it became asymmetric along the three phase contact line under the influence of a turbulent flow.

1. Introduction

Flotation is an important particle processing technique using bubbles to separate hydrophobic particles from hydrophilic particles, based on the hydrophobicity difference. Valuable mineral particles are recovered by altering the hydrophobicity level of the particles, either naturally or chemically. Bubbles carry the mineral particles up to the froth layer and unwanted gangue particles come out in the tailings. The flotation process is characterized by three successive incidences: collisions between particles and bubbles, particle attachment to the bubble and particle detachment from the bubble. The detachment of particles leads to low recovery rates of the mineral particles. Two options exist to minimize the detachment of particles: decreasing the detaching forces coming from the turbulent flow by floating the particles in a calm and gentle environment, and increasing the attaching forces between the particles and the bubbles. The most significant contribution to the attaching force comes from the capillary force, and the successful recovery of mineral particles depends on the capillary forces between particles and bubbles.

The capillary force relies on the hydrophobic level of the particle, which is reflected by the contact angle. With higher hydrophobicity, mineral particles attach to bubbles more easily, and once attached, a close bond forms between the particle and the bubble. The capillary force is determined by three parameters: the surface tension of the fluid, the perimeter of the three phase contact line and the contact angle. It can be expressed as:

$$F_c = 2\pi\sigma R_p \sin\alpha \sin(\theta - \alpha) \tag{1}$$

where R_p is the particle radius, θ is the contact angle, α is the central angle of the three phase contact on the particle surface, and σ is the surface tension. The notations used can be found in Fig. 1 (Nguyen, 2003).

The contact angle is of great importance in measuring the floatability of mineral particles. As important and useful as they are, contact angles can be frustrating to measure and complex to interpret (Decker et al., 1999). Conventionally, a contact angle is measured inside the liquid phase, where a liquid/vapour interface meets a solid interface. The structure of the three phase intersection is shown in Fig. 2, and it is categorized into three ranges: nano scale range, transition range and macroscopic range (Starov, 2010). The nano range is the liquid film in front, as is shown in Region 4. The transition range consists of two parts: Region 2, where a spherical shape is distorted by the hydrodynamic force; and Region 3, where Derjaguin's pressure comes into play and dominates at the end of the region. The macroscopic range is the meniscus of liquid/vapour interface at Region 1. The contact angle is measured

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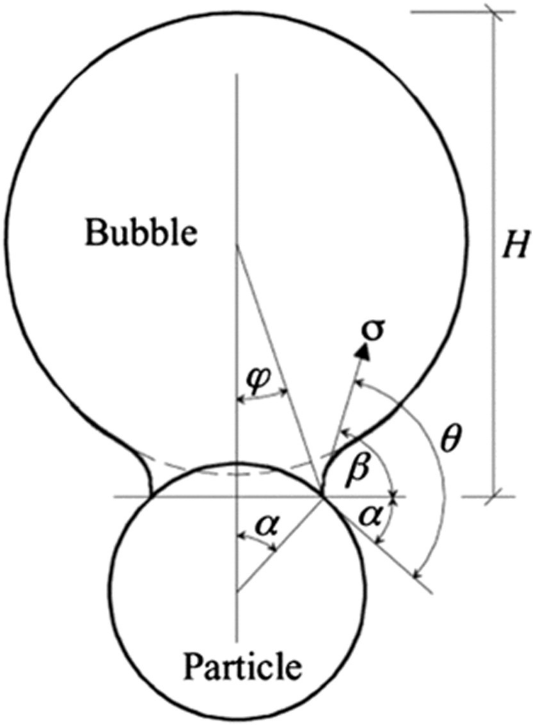

Fig. 1. Axisymmetric geometry of the particle attached to bottom a bubble (Nguyen, 2003).

at the intersection by the angle between the tangent of the spherical part of the liquid/vapour interface and the solid interface.

The techniques of contact angle measurement were reviewed (Chau, 2009), and the contact angle measurement techniques are generally categorized into two groups: measurements on flat plates and measurements on non-ideal surfaces. Measuring the contact angle on a flat plate and attributing it to mineral particles is questionable, with Hunter (2001) describing it as useless, and possibly misleading. Measuring the contact angle of a single particle is challenging, and generally an averaged contact angle is measured on a packed bed of particles. However, efforts have been made to measure the contact angle on single particles. For example, atomic force microscopy (AFM) has been used to measure the contact angle of small particles (Nguyen et al., 2003; Preuss and Butt, 1998). The contact angle of solid particles can be influenced by many physical and chemical factors (Chau et al., 2009), making it insufficient as a resemblance of particle floatability. A single bubble Hallimond microflotation cell was used to determine the contact angle (Drzymala, 1994; Kowalczuk and Drzymala, 2011), where the maximum floatable particle size and the balance of the forces were used to calculate the advancing contact angle.

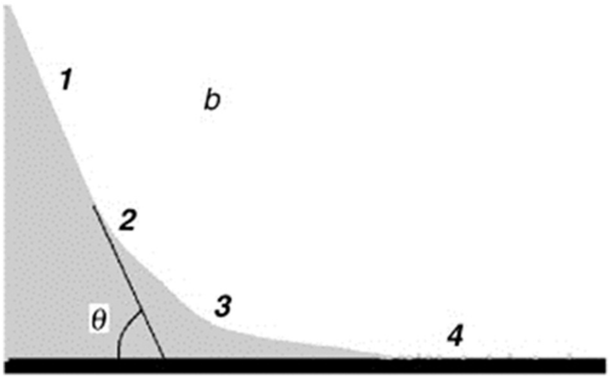

Fig. 2. A magnification of the vicinity of the moving apparent three phase contact line in the case of complete wetting: 1 — spherical part of the drop, which forms a dynamic contact angle, θ, with the solid substrate; 2 — a region, where a spherical shape is distorted by the hydrodynamic force; 3 — a region, where Derjaguin's pressure comes into play and become increasingly important towards the end of the region 3; and 4 — a region, where a macroscopic description is not valid anymore and surface diffusion takes place. (Starov, 2010).

The model (Eq. (1)) is used to calculate the capillary force, with the assumption that the contact angle is constant along the three phase contact line. However, the flow field in a mineral flotation environment is in a turbulent regime and the contact angles distributed along the three phase contact line vary significantly. Therefore, it is essential to obtain an understanding of the dynamic contact angle as a function of the system hydrodynamics to accurately predict the stability of the bubble–particle aggregate. Nevertheless, measuring a dynamic contact angle in a fluctuating flow field is a rather challenging task. Generally, dynamic contact angles are measured using two different approaches: changing the volume of the droplet or using a tilt cradle. Dynamic contact angles have proved to be dependent on the movement of the three phase contact, which is influenced by the turbulent fluid's motion (Gao and McCarthy, 2006; Johnson et al., 1977; Ngan and Dussan, 1982). Blake et al. (1999) investigated the influences of the hydrodynamics on the measurement of the dynamic contact angles. The wetting speed and the flow field in the vicinity of the moving contact line were found to be influential in the dynamic nature of the contact angles.

The advancing contact angle or the receding contact angle can be measured when the three phase contact line either contracts or spreads. The contact angle hysteresis (Δθ) is the advancing contact angle minus the receding contact angle. The surface roughness and heterogeneity (Oliver et al., 1980; Schwartz and Garoff, 1985) as well as the packing structure and organization of the molecules on the solid surface (Neumann, 1974; Yasuda et al., 1994) can make a difference to the dynamic contact angle measurements. Pitois and Chateau (2002) analysed the effects of contact angle hysteresis on the force and the work of removal of a particle from a water/air interface. The pinning effect of the contact line was found to affect the capillary force. In flotation, the contact angle of a bubble–particle aggregate has a spectrum of values, ranging from an advancing to a receding contact angle. Hence, the instantaneous capillary force changes with the dynamic contact angle. To successfully predict the bubble–particle aggregate's stability, therefore, an accurate measurement of the dynamic contact angle is necessary to determine the correct magnitude of the capillary force. Acknowledging the dearth of knowledge in this area, the present study aims to measure the dynamic contact angle of a bubble–particle aggregate in a turbulent flow field when the bubble detaches from the particle. The emphasis is on measuring the changes of the dynamic contact angle and explaining its role in the process of bubble–particle detachment.

2. Experimental procedure

2.1. Materials

The materials used were Milli-Q water for the liquid, whilst atmospheric air was used for the bubble. A stainless steel ball with a diameter of 3 mm was used as a particle from which a bubble was detached. The particle had a hole drilled through the centre and was anchored on the top of a needle (G32), and the needle was bent horizontally, as is shown in Fig. 4(b). With continuous air supply from the capillary system, a single bubble formed and grew from the hole at the particle's equator. When the bubble was sufficiently large, it slid to the top of the particle because of the buoyancy effect. Therefore, a closed single bubble–particle aggregate can be generated. The stainless steel particles were immersed in acetone for 10 min and in ethanol for 10 min, and then rinsed with large amounts of Millipore water. The balls were cleaned before the experiments and used immediately.