International Journal of Mineral Processing 142 (2015) 22–29

Contents lists available at ScienceDirect

International Journal of Mineral Processing

journal homepage: www.elsevier.com/locate/ijminpro

Instantaneous bond number for a particle detaching from a bubble

Guichao Wang [a,b], Ya Gao [b], Subhasish Mitra [b], Yanfeng Li [b,c], Shenjie Zhou [a,*], Geoffrey Evans [b,*]

[a] School of Mechanical Engineering, Shandong University, Jinan, Shandong 250061, China
[b] School of Engineering, University of Newcastle, Callaghan, NSW 2308, Australia
[c] School of Chemical Engineering and Technology, China University of Mining and Technology, Xuzhou, Jiangsu 221116, China

ARTICLE INFO

Article history:
Received 12 September 2014
Received in revised form 9 November 2014
Accepted 17 March 2015
Available online 10 April 2015

Keywords:
Particle bubble detachment
Bond number
Flotation

ABSTRACT

In almost all mineral flotation systems the particles and bubbles are brought into contact with each other under turbulent flow conditions which although beneficial in promoting particle–bubble collisions, at the same time increase the probability of particle detachment. Often the detachment of a particle is described in terms of a modified Bond number (expressed as ratio of attachment force to detachment force) greater than 1.0 however very few studies include attachment force in the numerical modelling. Acknowledging the dynamic interaction of bubble–particle aggregate in an actual flotation system, in this work, a dynamic model of the particle motion on the bubble interface was developed based on Schulze's theory considering contributions from gravity, buoyancy, pressure force, capillary force and the fluid drag. The purpose of this modelling was to check the consistency of the particle detachment criterion at Bond number greater than 1.0. Transient magnitudes of both the attaching and detaching forces were presented and the resulting temporal variation of the Bond number was reported. It was found that during the process of particle motion, although the Bond number exceeded the limiting value of 1.0, the particle still remained attached to the bubble interface. It appears that the criterion holds good only for a steady state case when the Bond number remains less than 1.0 and not for a dynamic case where the Bond number may exceed 1.0.

1. Introduction

Froth flotation has been used for over a century to separate valuable mineral particles based on their hydrophobicity difference. It is extensively employed for mineral beneficiation purposes. According to Ruthven (1997), approximately one billion tons of mineral ores are treated annually by this method. The fundamental basis of successful recovery of mineral particles is the interaction between particles and bubbles. In the flotation process, both particles and bubbles are required to be brought into close contact which is defined as the collision process. This is followed by rupture of the thin liquid film between the colliding particle and the bubble which leads to the formation of three-phase contact line (TPCL). The particle, due to its inertia penetrates farther into the bubble with expansion of the TPCL until equilibrium is obtained between the attaching and detaching forces. If the particle has a higher inertia or turbulent intensity of the surrounding fluid is too strong, the capillary force (attaching force) cannot hold the particle to the interface and eventually the particle detaches (Ralston et al., 1999). It is widely acknowledged that the satisfactory operation of the froth flotation process relies on the nature of bubble–particle interactions and that a deeper understanding of the dynamics of this interaction process involving various forces can improve the process performance better.

As mentioned before, the performance of the flotation process depends on the attachment of the particles onto the bubble interface, it is critical to quantify the attractive force between the bubble–particle pair. With the aid of surface force measuring techniques such as atomic force microscopy, a large amount of experiments have been conducted to study particle–bubble interactions in stationary liquid (Ally et al., 2010; Butt, 1994; Johnson et al., 2006; Taran and Nguyen, 2012).

Experimentally, the particle dropping technique on a stationary anchored bubble has been applied to directly observe particle–bubble interaction and attachment at the microscale (Nguyen and Evans, 2004b; Verrelli et al., 2012; Verrelli et al., 2011; Wang et al., 2003). However, due to the complexity of the flotation phenomenon, the principles governing bubble–particle interaction are not yet fully understood despite many decades of research.

Alternatively, numerical simulations have become a widely recognised tool to investigate such a complex phenomenon. Previously, bubble–particle interaction was studied in a quiescent liquid in the framework of the Basset–Boussinesq–Oseen (BBO) equation (Nguyen and Evans, 2004a; Nguyen and Schulze, 2004; Verrelli et al., 2012) where only gravity, buoyancy and drag force were considered to influence particle motion. It is noted that these studies simulated a Stokesian particle falling in a quiescent liquid under gravity where the particle slides over the bubble interface and eventually detaches at the base of

* Corresponding authors.
E-mail addresses: zhousj@sdu.edu.cn (S. Zhou), Geoffrey.Evans@newcastle.edu.au (G. Evans).

http://dx.doi.org/10.1016/j.minpro.2015.03.012
0301-7516/

the bubble. These modelling studies however did not simulate the influence of any attachment force.

It is emphasised that it is the selective attractive force between the bubble interface and particles that aid in recovery of desired products. This attractive nature arises due to both long range (capillary force) and short range attractive forces (hydrophobic force, van der Waal force, electric double layer force). When long range forces are of prime interest, capillary force remains the dominant factor in such interactions that govern the stability of the bubble–particle bubble system (Schulze, 1977). Being adhesive in nature, capillary force accounts for the particle–liquid interactions and also includes hydrophobicity of the particle surface by means of contact angle.

In the detachment process, capillary force is not enough to counterbalance the contributions of all detaching forces. Schulze (1982) proposed a modified Bond number (Bo^*), defined as the ratio of attachment force to detachment force to describe the detachment process. The Bond number used in his study was a modified form of the definition of the conventional Bond number. In a more conventional sense, the Bond number (Bo), named after English physicist Wilfrid Noel Bond, can be expressed as a dimensionless number representing the ratio of body force to capillary force. Originally defined to characterise the shape of typical two phase entities such as bubbles and droplets, Bo can be written in terms of density, ρ, surface tension, σ, gravity, g, and characteristic length, l, as:

$$Bo = \frac{\rho g l^2}{\sigma}. \qquad (1)$$

The modified Bond number used in Schulze's theory characterises the stability of particle–bubble aggregate by specifying equilibrium of forces which yields $Bo^* = 1.0$. When Bo^* is less than 1: the sum of the detaching forces is less than the attaching forces and the particles remain attached to the bubble. Conversely, when Bo^* is greater than 1.0, the sum of the detaching forces exceeds the magnitude of the attaching forces resulting in detachment.

In this work, we present a two dimensional model for particle–bubble interactions in a quiescent liquid. An instantaneous force balance comprising gravity force, buoyancy force, capillary force, pressure force and drag force was developed to determine particle motion on a stationary bubble interface. Two cases were simulated: (1) when the particle remained attached to the bubble interface and (2) when the particle detached from the bubble interface. The transient variation of the modified Bond Number was reported in both cases. Also, the resultant motion (trajectory and velocity) of the particle was computed for both cases and compared with reported experimental data.

2. Numerical methodology

To understand particle detachment from a bubble, it is important to explicitly quantify the interactions between the particle and the bubble. A mathematical model is developed to quantify the particle trajectory for a single bubble–particle system using Schulze's theory (Schulze, 1993). Of interest to this study is the position of the centroid of the particle to the centre of the bubble as a function of time. Considering a particle with initial position, the new position of the particle at time t, being subjected to resultant acceleration, is given by:

$$\vec{S}_{(t+\Delta t)} = \vec{S}_{(t)} + \vec{u}_{(t)}\Delta t + \vec{a}_{(t)}\Delta t^2 \qquad (2)$$

where $S_{(t)}$ is particle initial position at time t, $S_{(t+\Delta t)}$ is particle position at time $t+\Delta t$, is particle acceleration velocity at time t and $u_{(t)}$ is particle velocity at time t. A schematic representation of a particle bubble aggregate is shown in Fig. 1. Under quiescent conditions, the dynamic motion of an attached particle on a stationary bubble surface can be

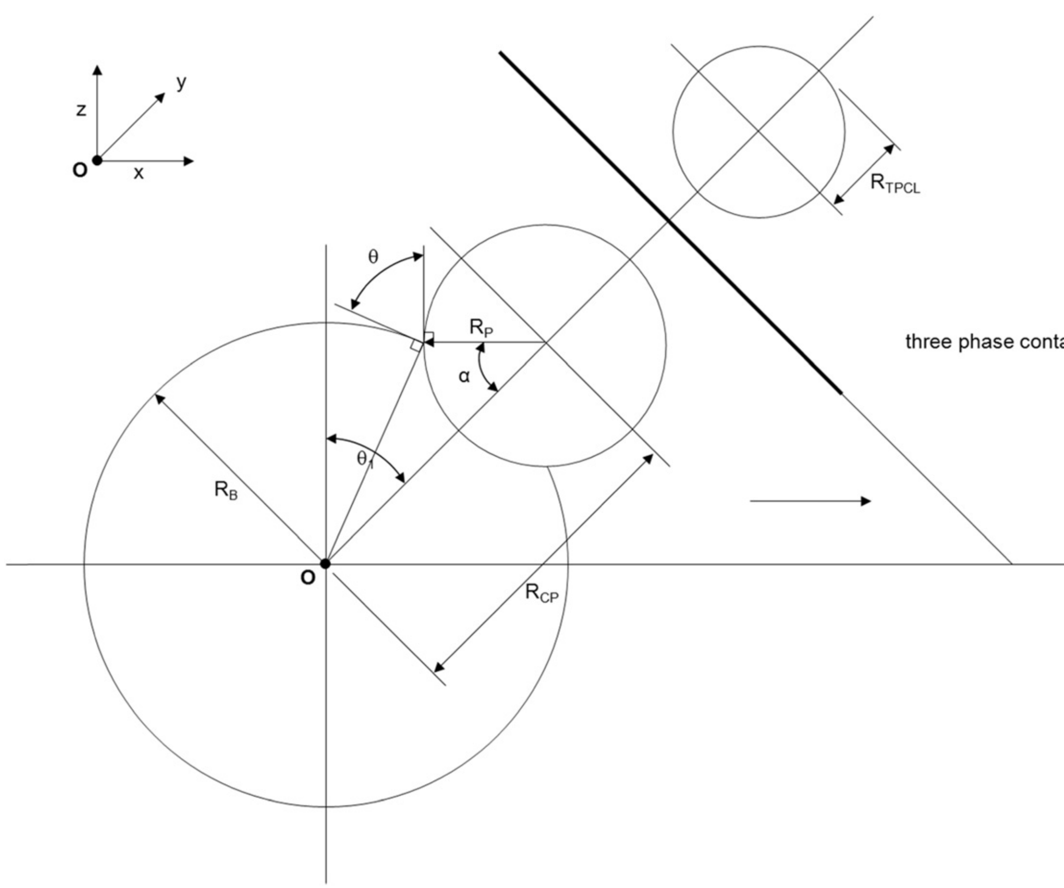

Fig. 1. Schematic of particle sliding on bubble surface.