Colloids and Surfaces A: Physicochem. Eng. Aspects 498 (2016) 258–267

Contents lists available at ScienceDirect

Colloids and Surfaces A: Physicochemical and Engineering Aspects

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

Effect of bubble size and velocity on collision efficiency in chalcopyrite flotation

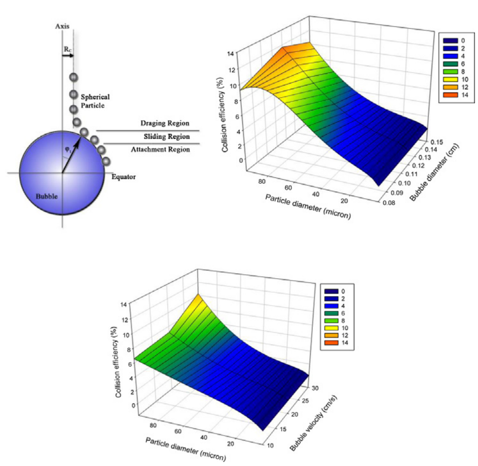
Ahmad Hassanzadeh[a,*], Behzad Vaziri Hassas[b], Sabri Kouachi[c], Zuzana Brabcova[d], Mehmet S. Çelik[a]

[a] Mineral Processing Engineering Department, Faculty of Mines, Istanbul Technical University, Maslak 34469, Turkey
[b] Department of Metallurgical Engineering, College of Mines and Earth Science, University of Utah, 135 South 1460 East, Rm 412, Salt Lake City, UT 84112, USA
[c] Applied Chemistry and Materials Technology Laboratory, Larbi Ben M'hidi University, OEB 04000, Algeria
[d] Smart Materials and Surfaces Laboratory, Faculty of Engineering and Environment, Northumbria University, Newcastle upon Tyne, Ellison Place, NE2 3AE, United Kingdom

HIGHLIGHTS

- Collision efficiency of particle- bubble pair is determined under the given conditions.
- Effect of bubble size, velocity and particle size on collision efficiency is shown.
- Collision efficiency is classified and discussed in different conditions.
- An index is suggested to account for the effect of inertial forces in collision efficiency.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 24 January 2016
Received in revised form 28 February 2016
Accepted 13 March 2016
Available online 17 March 2016

Keywords:
Bubble velocity
Bubble diameter
Collision efficiency
GSE
Schulze model

ABSTRACT

In flotation processes, bubble diameter (d_b), bubble velocity (v_b), and turbulence are the key factors involved in particle-bubble interactions. The collision efficiency (E_C) is used as an indicator to assess the extent of these interactions. In this work, the bubble surface is assumed mobile with potential flow conditions dominating the particle-bubble collision efficiency. The collision probability has been determined by Schulze and Generalized Sutherland Equation (GSE) models in the particle size range of 1–100 μm. Bubble diameters of 0.08, 0.12, and 0.15 cm and bubble velocities of 10, 20 and 30 cm/s were selected to study the flotation of chalcopyrite. The results reveal that the collision efficiency of ultra-fine particles (1–10 μm) is generally improved with bubbles of finer sizes, e.g. d_b = 0.08 cm compared to those of larger sizes, i.e. d_b = 0.12 and d_b = 0.15 cm. Also, in the same particle size range, E_C decreases with increasing the bubble velocity. The best agreement between Schulze and GSE models for ultra-fine particles at all bubble

* Corresponding author.
E-mail address: hassanzadeh@itu.edu.tr (A. Hassanzadeh).

http://dx.doi.org/10.1016/j.colsurfa.2016.03.035

sizes is achieved at the bubble velocity of 30 cm/s. The maximum E_C of chalcopyrite (0.12) using the GSE model is found to occur for coarser particles of 70–100 μm in size at bubble conditions of v_b = 30 cm/s and d_b = 0.12 cm. Results reveal that for a given bubble diameter increasing the bubble velocity from 10 to 30 cm/s makes the inertial force more effective on finer particles. A detailed interpretation of the effect of bubble diameter and its velocity on particle-bubble interaction of chalcopyrite is discussed from a theoretical point of view.

1. Introduction

Bubble-particle interactions are widely shown to be the most important sub-process in froth flotation. These interactions are quantified based on statistical approaches on successful transfer of particles on bubbles towards the froth phase and concentrates. Capture efficiency (E_{cap}) or collection efficiency is composed of the probability of three sub-steps (Eq. (1)) [15,7,30,11].

$$E_{cap} = E_c \times E_a \times E_s \quad (1)$$

where *Ec*, *Ea*, and *Es* are collision, attachment, and stability (detachment) efficiencies, respectively. A deep understanding of these microprocesses is fundamentally necessary in predicting rate constant of flotation kinetics [8,4,15,28,21].

The collision efficiency (E_C) (also called capture efficiency) is defined as the ratio of the number of the particles encountering a bubble per unit time, to the number of particles approaching the bubble at a long distance in a flow tube with a cross sectional area equal to the projected area of the bubble (Eq. (2)) [39].

$$E_c = \left(\frac{d_c}{d_b}\right)^N \quad (2)$$

where d_c and d_b are the particle and bubble diameters, respectively. The definition given by Schulze specifies N as equal to two.

It is widely accepted that, particle–bubble encounter in flotation is the first and the most important step between the sub-processes of particle–bubble interactions which directly affect flotation rate constant and thereupon flotation recovery [29,11,35]. This sub-process, in turn, is mainly dominated by hydrophobic interactions [18] and hydrodynamics conditions inside a flotation cell. In fact, the nature of bubble-particle collision is determined by the relative velocity of bubble and particle, the contribution of turbulence to velocity fluctuation, bubble and particle sizes, and particle density. In other words, the E_C between two spheres of a given diameter is in the form of Eq. (3) as follows.

$$E_C = f\left(\rho_p, d_p, Re_b\right) \quad (3)$$

where E_C is a function of particle density (ρ_p), particle diameter (d_p) and the bubble Reynolds number (Re_b) which can be calculated from the terminal rise velocity given the bubble size and the load of solids, as represented by Eq. (4).

$$Re_b = \frac{d_b V_b \rho_w}{\mu_w} \quad (4)$$

where d_b is bubble diameter, v_b denotes bubble velocity, ρ_w and μ_w, are specific gravity and viscosity of water, respectively.

The streamline regime and its function for spherical particle motion around a bubble change if Stokes or potential flow conditions prevail. For example, if we consider one particle of which $d_p = 0.1(d_b)$, under Stokes streamline function, collision will happen only when the particle is on streamline that has closest approach to the bubble less than or equal to the radius of the particle. So, it can be concluded that a neutrally buoyant particle of diameter $d_p = 0.1(d_b)$ must be no more than about 17% of a bubble radius off the center line of the collision path if it is to make contact with the bubble surface during the flypast under Stokes flow. On the other hand, a neutrally buoyant particle of the same size will touch the bubble surface if it is as far out as 56% of the bubble radius under potential flow conditions. Obviously, the collision efficiency (E_C) for particles of this size is quite small in either case but significantly lower for Stokes flow [19].

The motion of bubbles in a flotation cell and their collision with particles demonstrate the most significant component governing the overall flotation kinetics. As a result, over the last several decades in flotation processes, bubble diameter and its velocity were considered important parameters in studying bubble-particle interactions [24,49,22,40]. For instance, it is shown that the flotation rate increases up to one hundred-fold when the bubble size is reduced from 655 to 75 μm [1]. Reay and Ratcliff [31] investigated the case of bubbles of less than 0.10 mm in diameter and particles of less than 20 μm. After calculating the E_C in terms of some assumptions they concluded that when ρ_p/ρ_f is 1 and 2.5, N equals to 1.9 and 2.05, respectively. Other researchers also reported that the probability of collection for coal increased sharply with decreasing bubble size [48]. Shahbazi et al. [36,37] experimentally showed that quartz particles can achieve a maximum collision probability of around 48% with an impeller speed of 1100 rpm, air flow rate of 15 l/h and particle sizes of 545 μm. When the particle size was changed to 50 μm and air flow rate to 30 l/h, the maximum collision probability was reduced to 5%. Dai et al. [6] conducted experimental investigation on quartz particles for two different cases i.e. d_b = 0.15 cm, v_b = 31.6 cm/s and d_b = 0.077 cm with v_b = 19.6 cm/s and found good agreement between their results and the GSE model. Li and Schwarz [23] used a computational fluid dynamics (CFD) method to study the E_C in turbulent flow. They utilized the experimental results published by Dai et al. [6] for quartz particles. The simulation results of this study showed that the bubble wall effect is significant for particles larger than 30 μm and the bubble wall effect must be considered to achieve accurate predictions. In fact, bubble surface disturbs the creeping flow around a particle when it approaches the bubble surface. This particle-wall interaction (the bubble wall effect) known as short-range hydrodynamic interaction is a function of particle-wall distance. However, for particles coarser than 55 μm, the E_C is reduced by more than a factor of two by the wall effect because of the significant increase of the force opposing particle deposition. Although the effect of bubble diameter is mentioned in various experimental and theoretical investigations, its role along with the effect of bubble velocity on E_C has not been clarified [1,12,29,16,32].

In most practical studies, a bubble is pinned at the tip of the capillary, and its surface is recorded by a high-speed camera while it is approached by particles settling inside a stagnant liquid [46,18]. Since such experiments do not consider liquid flow, the collision of particles with bubble is solely based on the settling velocity of particles.

Many researchers have focused on modeling of collision sub-process [5,26,20]. In fact, different collision efficiency models have been suggested, however, due to the complexity involved in nature of this process, it is necessary to utilize both accurate and simplified models. Even though all of these models estimate that the