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Influence of the propagation of three phase contact line on flotation recovery

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ABSTRACT

Froth flotation is considered the most effective process of beneficiating low grade ores and is widely used in the base metals industry. For effective flotation, the attachment of mineral particles to air bubbles is important and has been studied by many researchers by measuring quantities such as attachment time, film-thinning time and induction time. This paper identifies an important step in the bubble–particle attachment process, namely, the expansion mechanism of the three phase contact (TPC) line between liquid, solid and air. It has been shown that the TPC expansion time is determined by the drainage of the surrounding fluid. It is influenced by factors such as pulp chemistry surrounding the particle, variations in surface forces and pressure inside the bubble. It has been observed experimentally that the TPC expansion time bears square root relationship to attachment efficiency. In this work, it has been argued that the attachment efficiency is related to the TPC circle radius propagation.

1. Introduction

Flotation is widely used physicochemical process in mineral processing and chemical industries to separate particles with different surface properties by selectively attaching them to air bubbles. First the particle surfaces are conditioned to render them hydrophobic using collectors and suspended in a pulp through agitation. Air is then introduced along with a frother to generate sufficiently small air-bubbles. The moving particles collide with and attach to air bubbles. The mineral particles are then recovered when the particle-laden air bubbles rise to the surface forming a froth layer. For that reason, the process of bubble–particle attachment is a critical stage that determines the efficiency of the overall flotation process. It involves several stages: the approach of the bubble and particle towards each other, the draining of the liquid film between bubble and particle to a critical thickness so that rupture occurs forming a three phase contact (TPC) between air, mineral and liquid, the propagation of the three-phase contact line to form a stable attachment of the particle to the air bubble. Initially, researchers lumped the time for these sub-processes to occur as *induction time* and related the flotation recovery to induction time (Jowett, 1980; Yoon and Yordan, 1991). However, more recently the induction time has been split into its components (Gu et al., 2003). Nguyen et al. (1997) defined the induction time (t_{ind}) as attachment time (t_{att}) that comprise of three components (Wang et al., 2005; Albijanic et al., 2010b):

$$t_{ind} = t_{att} = t_d + t_r + t_{tpc} \quad (1)$$

where t_d is the time for liquid drainage to critical thickness, t_r is the time for rupture to form the TPC and t_{tpc} is the time for TPC expansion to establish a stable wetting perimeter.

Considering the drainage time as the induction time, Schulze (1984) proposed a model for the induction time in terms of liquid drainage between two plane-parallel discs using Reynolds equation. Wang et al. (2005) have used a similar approach but considered the drainage between a spherical particle and a spherical bubble. The effect of the pulp chemistry has only been included implicitly through the driving pressure drop in the former and critical rupture thickness in the latter, respectively. Ye et al. (1989) argued that the induction time is a kinetic measurement of the hydrophobicity and is more important than the traditional measure of hydrophobicity of contact angle. They considered the measured induction time to be comprised of time required to thin the water film to the critical thickness (τ_1) for rupture and the time to establish a stable attachment area i.e., TPC expansion (τ_2). They showed that time to rupture, τ_1, was much smaller than that for TPC expansion. This implies that the time for TPC expansion is of critical importance in determining the bubble–particle attachment and in turn the flotation recovery as the stability of the attachment is directly dependent on the perimeter of the contact line.

In the work, a model has been proposed to determine the time TPC expansion and its influence on flotation recovery. It involves a parameter that takes into account the effect of chemistry of the pulp that influences the driving pressure. Although numerous authors have studied the relationship between attachment time and flotation recovery, both bubble–particle attachment time and flotation recovery have been studied mostly as a function of one

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Nomenclature

Adj MS	adjusted means square	t_c	contact time
b_i, b_{ij}, b_{123}	regression coefficients	t_d	drainage time
D	effective diameter	t_{ind}	induction time
DF	degree of freedom	t_r	rupture time
E_a	attachment efficiency	t_{tpc}	time for TPC expansion
F and P	statistical parameters	V	volume drained of liquid during attachment process
k	rate constant	V_p	particle volume
R	particle radius or flotation recovery	x_i	investigated factors
r	radius of TPC circle	α	TPC expansion parameter
Seq SS	sequential sum of squares	μ	liquid viscosity
t_{att}	attachment time	$\Delta P/\Delta L$	pressure gradient

selected factor at a time while other factors, such as particle size, pH, ionic strength, concentration of surfactants, bubble size, and pulp temperature, have been kept constant. The main limitation of such approaches is not detecting the interactions occurring between two or more factors, and hence the detailed information about sensitivity of bubble–particle attachment time to predict flotation response has not been examined. For that reason, this study also focuses on investigating the effects of three commonly used variables i.e., collector, pH and activator, on the TPC expansion parameter based on a full factorial design. The factors studied are collector (dodecyl amine hydrochloride) and activator (potassium chloride) concentration as well as solution pH.

2. Previous work

Bubble–particle attachment time can be measured using several techniques such as the Glebotsky induction timer (Glembockij, 1953), the wetting film stability measurements (Letocart et al., 1999) as well as using models to back calculate attachment time from flotation data (Danoucaras et al., 2013; Min and Nguyen, 2013). Nevertheless, the Glembotsky induction timer has been mainly employed by numerous researchers (Yoon and Yordan, 1991; Fuerstenau and Jia, 2004; Albijanic et al., 2010a) who found the strong relationship between attachment time and flotation recovery i.e., the highest flotation recovery occurs at the shortest attachment time. The Glembotsky technique is based on keeping a captive bubble in contact with a bed of mineral particles at different contact times, and then the relationship between numbers of successful attachment (i.e., attachment efficiency) at different contact time is obtained. The contact time at which numbers of successful attachment is 100% (Albijanic et al., 2011, 2012) is used as attachment time.

Bubble–particle attachment time is commonly determined using pure minerals such as quartz (Yoon and Yordan, 1991) or coal (Ye et al., 1989), and it was found that bubble–particle attachment time is strongly affected by physical properties of minerals (particle density, size and shape), solution chemistry (pH, dissolved ions and surfactant concentration), bubble size and temperature of solution. These findings are summarized recently by Albijanic et al. (2010b). The most important conclusions of the studies investigating attachment time of pure minerals are as follows:

- The solution chemistry conditions (pH, dissolved ions and surfactant dosage) change the surface properties of particles which influence the attachment time (Gu et al., 2003; Yoon and Yordan, 1991).
- Minerals with different composition at a fixed solution chemistry condition may also have different attachment time (Peng, 1996; Ye et al., 1989).
- The higher the solution temperature, the shorter the attachment time between a bubble and a particle because the viscosity of liquid decreases with the increase of temperature (Lazarov et al., 1994).
- The higher the bubble or particle size, the longer the attachment time since it takes longer time for the displacement of wetting film on the surface of bubbles or particles (Yoon and Yordan, 1991; Ye et al., 1989).
- The sharp-edged particles have shorter attachment time than spherical particles because sharp edges facilitate the thinning of wetting film (Dippenaar, 1982).

As regards modelling of attachment time from first principles, the Stefan–Reynolds model (Reynolds, 1886) has been used to describe the drainage of wetting film between a bubble and a particle because bubble surface is immobile in the presence of surfactant (Cha et al., 2011). In the Stefan–Reynolds model, the driving force represents the difference between the capillary pressure and the disjoining pressure. The disjoining pressure comprised a sum of DLVO (Derjaguin–Landau–Verwey–Overbeek) forces which are due to the van der Waals and electrical double-layer interactions (Schulze et al., 2001) and non-DLVO hydrophobic interactions (Yoon, 2000). However, the successful prediction of attachment time remains a challenge since the extension of the classical DLVO theory using hydrophobic force has not been successful (Christenson and Claesson, 2001; Ninham, 2006).

3. Theoretical development

Once the liquid film between a particle and an air bubble is drained to the critical thickness during their relative approach, rupture will occur and a nucleic hole of the TPC between air, liquid and mineral will be formed at the point O as shown in Fig. 1. The particle will then be attached to the air bubble due to the interfacial forces along the TPC line. Initially the perimeter of the TPC line will be small and effective attachment will not occur. However, if the contact is maintained between the bubble and particle, the TPC line will propagate/expand by the drainage of the fluid film between them due to the pressure inside the bubble and surface tension forces that depend on the surrounding pulp chemistry.

Assuming that the bubble is large in comparison to the particle size which is the case in most practical applications of flotation, the curvature of the bubble may be neglected. The volume of liquid drained during the propagation of the TPC line may be represented by the volume, (V). It may be calculated as the volume generated by the revolution of area AOB about the vertical axis through O as shown in Fig. 1.

$$V = \int_0^r 2\pi r h dr = \int_0^r 2\pi r(R - R\cos\theta)dr \quad (2)$$