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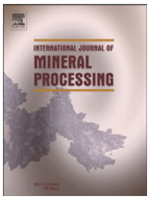

Modeling of bubble coalescence in saline water in the presence of flotation frothers

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ABSTRACT

This paper proposes a model based on the capillary wave theory of Valkovska, Danov and Ivanov to predict the lifetimes (τ) of small foam films confined between air bubbles in saline water containing flotation frothers such as sodium dodecyl sulfate (SDS), polypropylene glycol (PPG) with a molecular weight of 400, and methyl isobutyl carbinol (MIBC). The model considers the important issues of intersurface force, bubble size, surface tension, and film radius. The predicted τ values of these foam films were compared to the experimental ones. Under the assumption of tangentially immobile film surfaces, excellent agreement between model and experiment for τ was obtained for SDS and PPG, whereas τ was slightly under-predicted for MIBC. The model can be improved by adding an adjustable parameter that is related to the lateral diffusion constant and surface concentration of frother molecules at the air/water interface.

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1. Introduction

Froth flotation is a key process step in the extraction and concentration of valuable materials such as mineral species, oil, and organics. In flotation, a variety of reagents are added to an aerated aqueous suspension, in which the small particles (typically 10–500 μm) with poor wettability adhere to air bubbles and rise up to enter a froth phase, leaving the remaining materials behind. Froth stability plays an important role in determining the grade and recovery achieved from a flotation operation (Mathe et al., 1998; Neethling and Cilliers, 2003; Ata et al., 2003; Pugh, 2007). Despite its importance, the froth phase in flotation is not well understood (Nagaraj and Ravishankar, 2007). More and more flotation engineers recognize the importance of better understanding the stability of froth and, thereby, improving the performance of their flotation cells. However, relatively little is known of the fundamentals of froth stability and, therefore, it is difficult to model the froth behavior in flotation, with prediction of bubble coalescence in the froth phase remaining one of the most challenging tasks (Cillers, 2006).

Bubble coalescence in water or aqueous solutions has been the subject of numerous studies (Marrucci and Nicodems, 1967; Marrucci, 1969; Kirkpatrick and Lockett, 1974; Sagert and Quinn, 1978; Prince and Blanch, 1990; Samanta and Ghosh, 2011). In modeling bubble coalescence, Chen (1985) divided the coalescence process into three steps.

1) Approach of one bubble to another in an aqueous phase;
2) Formation and thinning of a thin foam film between two interfaces;
3) Rupture of the film as the thickness of the film becomes sufficiently small.

This subdivision can be used to describe the bubble coalescence process in flotation since approaching two air/water interfaces laden with micrometer-sized solid particles would lead to the formation of a particle-free thin foam film, with all the particles being expelled into the thicker meniscus region (Qu, 2012). The first step (approach of bubbles) is controlled by the hydrodynamics of the system. When two bubble contact with each other in water, they deform and create lamellae (thin film) and Plateau borders. The capillary pressure at the meniscus of a film serves as the driving force for the initial thinning of the film (in the second step). When the film thickness is below approximately 100 nm, the thinning process is controlled by surface forces. An attractive surface force tends to accelerate the film thinning process and the growth of film surface waves, which is conducive to film rupture, and vice versa with a repulsive surface force. In the framework of the celebrated Derjaguin–Landau–Verwey–Overbeek (DLVO) theory (Derjaguin and Landau, 1941; Verwey and Overbeek, 1948), the van der Waals force and electrostatic double-layer force are the two components of the intersurface force (or disjoining pressure). The van der Waals force in a thin free film is attractive and has been considered the primary mechanism leading to film rupture (Vrij, 1966; Vrij and Overbeek, 1968; Ivanov et al., 1970; Sharma and Ruckenstein, 1987; Erneux and Davis, 1993; Ida and Miksis, 1996; Vaynblat et al., 2000). The DLVO theory is limited to explaining colloid stability at an intermediate electrolyte concentration range (Ninham, 2006). In the presence of surfactants, the fluid system becomes very complex. At relatively

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high surfactant concentrations, the DLVO theory could still be used to explain the stability of thin foam films between two air bubbles (Exerowa and Kruglyakov, 1998; Valkovska et al., 2002). At low surfactant concentrations, however, the DLVO forces are not sufficient to explain the observed experimental results, and it has been suggested to include a non-DLVO attraction force (Angarska et al., 2004; Karakashev and Nguyen, 2007; Tabakova and Danov, 2009; Wang, 2012a; Ivanova and Angarska, 2013). Recently developed bubble coalescence models (Chen, 1985; Li, 1996; Jeelani and Hartland, 1994; Sharma and Ruckenstein, 1987) considered the DLVO forces only, and no models have been specifically developed or can be simply modified to include the non-DLVO attraction force existing at low surfactant concentrations.

In flotation, low concentrations of bubble-stabilizing reagents called frothers are typically applied to produce transient froth. Among the commonly used frothers are methyl isobutyl carbinol (MIBC) and water-soluble polymers such as polypropylene glycols with molecular weights of 200 to 800. Ionic surfactants such as sodium dodecyl sulfate are used as both collectors and frothers in non-sulfide mineral flotation. Shortage of freshwater has driven some flotation plants to use salt water as flotation medium. The inorganic salts have frothing power under the hydrodynamic conditions for flotation and can significantly reduce the required dosage of organic frothers for attaining desired froth stability and optimal flotation performance (Klassen and Mokrousov, 1963; Castro et al., 2010, 2013). In an effort to address the challenge of predicting bubble coalescence in flotation with using saline water, we proposed a model with the non-DLVO attraction force taken into consideration to predict the lifetime of the saline foam films at low frother concentrations, commensurate with flotation practice. The model was derived from the capillary wave theory of Valkovska et al. (2002). The predicted lifetimes of very small foam films formed from saline water with various flotation frothers were compared with the experimental data. The results obtained in the present work are discussed to identify the basic factors affecting bubble coalescence in flotation.

2. Modeling approach

First, the intersurface force law (intersurface force versus film thickness) was determined using the dynamic method of Sheludko (1967). The capillary wave theory of Valkovska et al. (2002) that considers film thinning and the growth of surface waves concurrently was used to predict the critical rupture thickness (H_{cr}). Finally, we obtained the film lifetime by integrating the film drainage equation from an initial film thickness to H_{cr}.

2.1. Determination of intersurface force law

The dynamic method of Sheludko was used to determine the dependence of intersurface force on film thickness. The dynamic method was derived from the theory on the dynamics of fluid films confined between two circular flat solid discs, established by Stefan (1874) and Reynolds (1886). Sheludko and coworkers proposed describing the hydrodynamic behavior of the microscopic liquid films using the following equation (Sheludko, 1957, 1967; Sheludko and Platikanov, 1961):

$$-\frac{dH}{dt}=\frac{2H^3(P_c-\Pi)}{3\mu R_f{}^2} \tag{1}$$

where H is film thickness, t is drainage time, μ is dynamic viscosity (9×10^{-4} Pa · s), R_f is film radius, Π is the intersurface force (disjoining pressure) and P_c is the capillary pressure. Note that (P_c–Π) is the driving force for film thinning. Eq. (1) is usually called the Reynolds equation, although it should be correctly named as the Stefan–Reynolds lubrication approximation (Nguyen, 2000). In principle, the above Reynolds equation is applicable to plane-parallel foam films with tangentially immobile surfaces. It has been shown that this condition can be met by using very small films stabilized by a surfactant (Exerowa, and Kruglyakov, 1998; Langevin, 2000; Coons et al., 2005). Specially, some researchers stressed that the Reynolds equation is only applicable to foam films with R_f below 50 μm (Manev et al., 1997; Karakashev et al., 2010).

The dependence of intersurface force on film thickness is deduced using the rearranged Reynolds equation (Exerowa and Kruglyakov, 1998):

$$\Pi=P_c-\frac{3}{4}\mu R_f{}^2\frac{dH^{-2}}{dt} \tag{2}$$

where dH^{-2}/dt were obtained by differentiating the polynomial fit of H^{-2} versus t.

It is customary to assume that various contributions to the intersurface force are additive, so one can use the following equation to express the intersurface force in soap films (Bergeron, 1999):

$$\Pi=\Pi_{el}+\Pi_{vw}+\Pi_{\text{non-DLVO}} \tag{3}$$

in which Π_{el} is the electrostatic double-layer force, Π_{vw} is the van der Waals force, and $\Pi_{\text{non-DLVO}}$ is a non-DLVO force represented by the following relation (Rabinovich and Yoon, 1994; Yoon and Aksoy, 1999; Tabakova and Danov, 2009; Ivanova and Angarska, 2013):

$$\Pi_{\text{non-DLVO}}=-\frac{K_{232}}{6\pi H^3}. \tag{4}$$

Eq. (4) is of the same form as the van der Waals force:

$$\Pi_{vw}=-\frac{A_{232}}{6\pi H^3} \tag{5}$$

so that K_{232} can be directly compared to the Hamaker constant (A_{232}) for the interaction between two gas phases (or bubbles) **2** interacting in water **3** at a separation distance of H.

In the present work, we studied the foam films at a high electrolyte concentration (i.e., 0.1 M NaCl or above), where the electrostatic double layer repulsion was effectively suppressed ($\Pi_{el}\approx0$). So the first term on the right side of Eq. (3) can be ignored to obtain:

$$\Pi=-\frac{1}{6\pi H^3}[A_{232}(H)+K_{232}]. \tag{6}$$

With the electromagnetic retardation and electrolyte screening effects taken into account, one can calculate the Hamaker constant by using the following equation (Russel et al., 1989):

$$A_{232}(H)=\frac{3h_P\nu_e}{16\sqrt{2}}\frac{\left(n_2^2-n_3^2\right)^2}{\left(n_2^2+n_3^2\right)^{3/2}}F\left(\tilde{H}\right) \tag{7}$$

in which h_P is the Planck's constant (6.63×10^{-34} J·s), ν_e the main electronic adsorption frequency (3×10^{15} Hz), c the speed of light in vacuum (3.0×10^8 m/s), n_2 the refractive index of air, n_3 the refractive index of solution, $\tilde{H}$ is the dimensionless distance,

$$\tilde{H}=n_3\left(n_2^2+n_3^2\right)^{1/2}\frac{2\pi\nu_e H}{c}$$

and

$$F\left(\tilde{H}\right)=\frac{4\sqrt{2}}{\pi}\int_0^\infty\frac{\left(1+2\tilde{H}x\right)e^{-2\tilde{H}x}}{\left(1+2x^2\right)^2}dx. \tag{8}$$

The limits of F when $\tilde{H}$ approaches 0 and infinity are 1 and $4\sqrt{2}/\pi\tilde{H}$, respectively. At intermediate $\tilde{H}$ values, Eq. (8) can be approximated

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