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Predicting flotation behaviour – The interaction between froth stability and performance

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ABSTRACT

Froth behaviour has a major impact on the overall performance of flotation cells, with the froth controlling the water recovery and entrainment, as well as having a significant impact on the recovery. Froth stability, including bubble coalescence and the bursting of the bubbles at the froth surface, are the key drivers of froth performance. Even though the froth stability is hard to directly control, it is important to understand how this stability impacts froth performance parameters such as the water recovery. In this paper it is shown how a theoretical understanding of froth behaviour based on foam physics can be used to link stability to performance. The extent to which these simplified theoretical relationships can describe the complex behaviour seen in real flotation systems at both the laboratory and industrial scale are explored. The paper shows how bursting flux depends upon gas flux and how this influences the relationship between the gas flux and the water recovery.

1. Introduction

The performance of a flotation cells is the result of the complex interaction between phenomena in both the pulp and froth phases. The froth phase has a crucial role to play as it controls the amount of water recovered, and thus the amount of entrainment, as well as having a significant impact on the overall recovery. This is because the same coalescence and bursting of the bubbles that restricts the amount of water reporting to the concentrate, thus improving the grade, also allows particles to become detached from the bubbles, a portion of which will fall out of the froth and thus reduce the overall recovery of the cell via its impact on the froth recovery.

Understanding the link between froth stability and flotation performance is thus a key to being able to predict both the grade and recovery from these cells. In previous papers, models for various aspects of froth performance based on the fundamentals of foam physics have been introduced (Neethling et al., 2003a; Neethling, 2008; Neethling and Cilliers, 2008, 2009). The theory behind these models will be briefly described at the beginning of this paper. These models, though, require information related to froth stability as inputs. In particular, they require the air recovery and surface bubble size as inputs, both of which are directly related to the stability of the particle laden films within the froth.

This paper will thus take a brief look at some of the theory related to the stability of these films, mainly to illustrate some of the complexity involved in the theoretical prediction of froth stability. While theory is enough to give clues as to the type of stability relationships to be expected, the relationship between mineralogy, particle size, reagent dosage and the stability of the films and, ultimately, the macroscopic stability of froth, is currently not well enough understood for theoretical predictions to be made.

This paper will thus take a semi-empirical approach in which the effect of gas rate on the stability parameters is obtained from laboratory, pilot and industrial scale cells. These will then be combined with the theoretical froth performance models to predict how the changes in stability influence the trends in overall behaviour, with these predictions being compared to the actual experimental results.

Despite the importance of froth stability on the performance of flotation froths (Hadler and Cilliers, 2009) there has been limited attempts to develop fundamental understanding of the coupling between stability and performance. The overall aim of this work is to establish models how liquid recovery is influenced by changes in gas rate into the cell when the added complexity of its impact on stability is included.

2. The physics of froths

The theoretical predictions of the performance of flotation froths are based on the fact that they share much of the same physics as that of two-phase foams, the main difference being that the films in flotation froths are, to a large extent, particle stabilised rather than being directly surfactant stabilised.

Structurally these froths consist of bubbles separated by films, or

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lamellae, with these films meeting in threes at Plateau borders. As the interfaces of the Plateau borders curve sharply compared to any curvature of the films, capillarity will cause liquid to be sucked out of the films and into the Plateau borders until the films are thin enough that forces between the two film interfaces are able to counteract this suction. In two-phase systems this will be due to either electric double layer interactions or even direct steric interaction between the surfactant molecules, while in flotation froths the steric interaction between the particles loaded onto the films will provide much of the counteracting force. This suction of the liquid out of the films means that most of the liquid in a froth is to be found in the Plateau borders. These Plateau borders, in turn, meet at 4-fold vertices to form a network of interconnected channels. This means that, while the films are where most of the attached particles are located, the Plateau borders are where most of the liquid and unattached particles are to be found and are thus the focus of most of the modelling (Weaire and Hutzler, 1999).

2.1. Liquid drainage

In previous papers the modelling of liquid drainage in flotation froths has been described in detail (Neethling et al., 2000; Brito-Parada et al., 2012) and therefore only a brief description of the theory will be given in this paper. Within the Plateau border three forces need to be considered, namely gravity, capillarity and viscous dissipation. As Plateau border dimensions are small and flows are comparatively slow, inertial forces can be neglected and thus these forces can be balanced against one another in order to derive the foam drainage equation (Verbist et al., 1996) in which the liquid velocity vector, $\boldsymbol{v_l}$, is a function of the gas/bubble velocity vector, $\boldsymbol{v_g}$, and the cross-sectional Plateau border area, A:

$$\boldsymbol{v_l} = -\boldsymbol{k}_1 A - \frac{k_2}{\sqrt{A}}\nabla A + \boldsymbol{v_g} \tag{1}$$

where $\boldsymbol{k}_1 = \frac{\rho \boldsymbol{g}}{3C_{PB}\mu}$ and $k_2 = \frac{\sqrt{\sqrt{3}-\frac{\pi}{2}}\gamma}{6C_{PB}\mu}$.

ρ, μ and γ are the density, viscosity and surface tension of the fluid, respectively, and $\boldsymbol{g}$ is the gravity acceleration vector. C_{PB} is a dimensionless Plateau border drag coefficient; it will have a value of approximately 50 if the fluid gas interfaces are immobile, but lower values as the interfacial mobility increases. This form of the drainage equation assumes that the viscous drag is dominated by losses in the Plateau borders rather than the vertices. This assumption is valid for foams in which there is low interfacial mobilities, which is likely to be the case in flotation froths as the interfaces are coated in particles. In the derivation of the models described in Section 2.2 it is the vertical component of the liquid velocity that is the most important, which means that the vector notation is no longer required, especially for k_1, for which the component in the direction of gravity is used.

The liquid content, ε, is related to the Plateau border area by the length of Plateau borders per volume of foam, λ, which is, in turn, a function of the bubble radius, R_b (using the equivalent spherical radius of the average bubble volume):

$$\varepsilon = \lambda A \tag{2}$$

where $\lambda = \frac{k_\lambda}{R_b^2}$.

The pre-factor in this relationship, k_λ, is a function of the poly-dispersity of the bubbles, though for bubbles with a geometry of Kelvin cells it will be approximately 1.70 and for a random foam it will be (Kraynik et al., 2004):

$$k_\lambda = 2.047\frac{R_b}{R_{32}} + 0.024 \tag{3}$$

where R_{32} is the Sauter mean radius of the bubbles, with the ratio between the Sauter mean and volume average radius being a measure of the poly-dispersity of the bubbles, with k_λ thus being approximately 2.071 for random mono-dispersed foams. Kraynik et al. (2004) noted that this relationship is accurate within 1% for volume average diameters which are within a factor of ten of the Sauter mean diameter; it would require an extreme level of poly-dispersity to go beyond this limit.

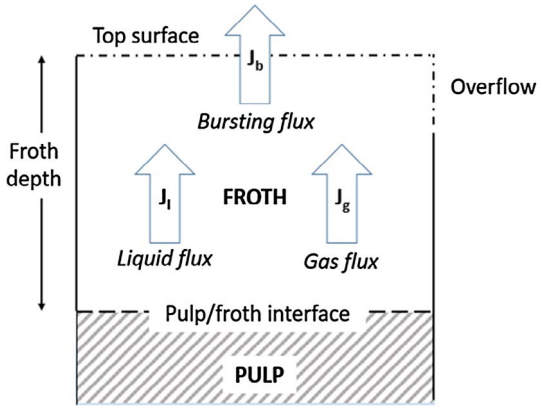

Fig. 1. Schematic of a typical flotation cell showing a section of the pulp and the froth phases and highlighting the top surface of the froth, the froth depth, i.e. the height of the froth above the interface, as well as the overflowing section above the lip of the cell. The liquid flux, J_l, gas flux, J_g, and bursting flux, J_b, are also shown schematically in the froth phase.

2.2. Liquid recovery from a flotation froth

The foam drainage equation can be solved for the case of an overflowing foam (a schematic of which can be seen in Fig. 1). The key boundary condition is the top boundary, which is that the vertical liquid flux at the top surface must be zero. The gas flux through this surface will depend on the air recovery, α (fraction of air entering the cell that leaves as unburst bubbles), and the drainage rate of liquid relative to the foam at the top surface must thus equal this flux:

$$J_g(1-\alpha) = k_1 A_{top} + \frac{k_2}{\sqrt{A_{top}}}\frac{\partial A}{\partial y}\bigg|_{top} \tag{4}$$

where J_g is the gas flux into the froth and A_{top} the cross sectional area of the Plateau borders at the surface of the froth.

Fig. 2 (from Neethling et al. (2003a)) shows a typical simulation of the Plateau border area as a function of foam/froth depth, which corresponds to a system in which gas flux is 0.5 cm/s and a bubble diameter of 1.5 mm. It can be seen that there is a change in the behaviour as the air recovery passes through 50%. A discussion on the physics behind this change can be found in Grassia et al. (2001).

This is reflected in the equations for the amount of water recovered, which follows different relationships depending on whether the air recovery is above or below 50%. It has been demonstrated in previous papers (Neethling et al., 2003a; Neethling, 2008; Neethling and Cilliers, 2009) that analytical approximations based on the foam drainage equation can be solved for the volumetric liquid flux, J_l:

$$J_l = \begin{cases} \frac{J_g^2\lambda_{out}}{k_1}(1-\alpha)\alpha & if\ \alpha < 0.5 \\ \frac{J_g^2\lambda_{out}}{4k_1} & if\ \alpha > 0.5 \end{cases} \tag{5}$$

where λ_{out} is the length of Plateau borders per volume based on an appropriately weighted overflowing bubble size. The approximation described in Eq. (5) holds for foams that are deeper than the capillary length scale, have viscous losses dominated by the Plateau borders and which have relatively low liquid contents in the overflowing foam (below about 5–10%), all of which hold for typical flotation froths. Most flotation froths, especially those in the rougher and scavenger banks, will have air recoveries below 50% (i.e. $\alpha < 0.5$).

In Neethling et al. (2003a,b) it was shown experimentally that Eq.