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Experimental studies and modeling of surface bubble behaviour in froth flotation

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ABSTRACT

Froth flotation is a versatile, widely used beneficiation technique employing air bubbles to selectively pick up certain particles in aqueous medium. The performance of the flotation process is significantly affected by froth stability and mobility, posing the need for precise control of the froth phase. The present paper aims to understand the motion of bubbles entering the froth phase from the pulp phase at different locations. The horizontal velocities of air bubbles across the top surface of the froth containing fine coal particles were measured. The results showed that at the region farthest from the froth discharge lip, no horizontal movement of the surface bubbles could be observed, and when approaching the lip there would be an increase in the horizontal velocity. The measured velocity profile was fitted to a froth model that considers the cumulative air recovery as a function of location. Six different types of cumulative air recovery functions were tested. The coefficient of determination (R^2) and the Akaike information criterion were applied to select the cumulative air recovery function with best fit to describe the horizontal velocity profile. The selected cumulative air recovery function was in a simple power-law form.

1. Introduction

Froth flotation is one of the most widely used particle separation techniques important to mineral and coal processing, waste paper recycling, and water treatment. In mineral industry, froth flotation is used to separate valuable fine mineral particles from the gangue. The flotation employs small air bubbles to selectively pick up the hydrophobic particles dispersed in water. The particle and air bubble aggregates in the pulp phase rise up and enter the froth phase where there are a number of sub-processes such as particle attachment, detachment, reattachment, liquid drainage, and bubble coalescence and bursting. The residence time of the aggregates in froth phase is considered an important factor affecting the flotation performance. Since the residence time is influenced by the behaviour of bubbles in the froth phase, it is essential to understand the motion of bubbles inside the froth phase.

Recent research progress found that flotation performance could have a strong correlation with air recovery, which is the fraction of air entering a flotation cell that overflows the froth discharge lip as unburst bubbles. For instance, Hadler et al. (2012) and Smith et al. (2010a,b) showed that peak air recovery (PAR) could indicate optimal flotation performance. However, air recovery gives little information on the motion of bubbles entering the froth phase from the pulp phase at different locations, from which the bubbles would have different residence times in the froth phase.

Some models have been developed to estimate the motion of the bubbles inside the froth phase based on measurable variables (Moys, 1979; Zheng et al., 2004; Zheng and Knopjes, 2004; Contreras et al., 2013). Moys (1979) described the bubble motion inside the froth phase using the Laplace equation. Murphy et al. (1996) and Cilliers and co-workers (Neethling and Cilliers, 2003; Brito-Parada and Cilliers, 2012; Cole et al.,

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2012) also used the Laplace equation to model the froth phase. However, the computational cost for solving the Laplace equation is relatively high. Moys (1979) also developed a simple transportation model based on mass balance equations. Similar approach was adopted by Zheng et al. (2004), Zheng and Knopjes (2004), and Contreras et al. (2013).

The aforementioned models corroborated well with the experimental results but many of them were only validated in two-phase foam systems (in the absence of solid particles). The solid particles can significantly affect froth stability and mobility by increasing the viscosity of the froth (Hunter et al., 2008) and the rigidity of the lamellae (Johansson and Pugh, 1992). Consequently, it is expected that the motion and velocity distribution of bubbles in the froth phase in the presence of particles is different from that in the absence of particles. Although Zheng et al. (2004), Zheng and Knopjes (2004), and Contreras et al. (2013) attempted to validate their transportation models using three-phase froth systems, the velocity measurements were carried out at only one or few positions across the froth surface.

In the present paper, we report the measured horizontal velocities of air bubbles across the froth surface of a laboratory-scale mechanical flotation cell fed with an aqueous suspension of fine coal particles. The experimental data were fitted to a froth model on the basis of the work of Contreras et al. (2013), incorporating a cumulative air recovery function. Two statistical methods were jointly used to select the best cumulative air recovery function to describe the surface velocity profile of the coal-laden froth. The implications of the present study for flotation cell design and operation are discussed.

2. Froth phase modelling

2.1. Model description

The main frame work of this study was based on the froth transportation model of Contreras et al. (2013). Briefly, the model has the following major assumptions:

i. The bubbles enter evenly (at a fixed flux) across the froth phase from the pulp phase;
ii. The velocity profile of the froth is determined by the motion of air bubbles in the froth phase;
iii. The gas holdup is constant throughout the froth phase;
iv. The thickness of the froth phase is constant.

Fig. 1 shows that the froth phase is divided into vertical and mixed transportation zones. In the vertical transportation zone, the bubbles (or froth) rise up vertically in plug-flow mode. Once the bubbles reach the level of the froth discharge lip, they enter the mixed transportation zone and start to move horizontally. A bubble sitting on the top surface of the mixed transportation zone can either burst or remain intact. The chance for a bubble to be recovered to the concentrate stream unburst would be related to the location of the bubble entering the pulp/froth interface, because a bubble rising closer to the lip is expected to have a higher chance to be recovered into the product froth.

The spatial horizontal velocity distribution can be obtained using a mass balance analysis for the mixed transportation zone (Fig. 1, R.H.S).

$$V_{in}(x) - V_{out}(x) = H_{out}(x) - H_{in} \quad (1)$$

where $V_{in}(x)$ is the flow rate of air arriving at the mixed transportation zone from the vertical transportation zone between 0 and x (normalised position, $= X/L$), $V_{out}(x)$ is the air flow leaving the mixed transportation zone by bubble bursting, H_{in} is the horizontal flow rate of air entering the mixed transportation zone, and $H_{out}(x)$ is the horizontal flow rate of air leaving the mixed transportation zone.

$V_{out}(x)$ can be expressed using $V_{in}(x)$ and the cumulative air recovery function, $f_{AR}(x)$:

$$V_{out}(x) = V_{in}(x) \cdot (1 - f_{AR}(x)) \quad (2)$$

where $f_{AR}(x)$ represents the fraction of the air entering between 0 to x that is recovered as unburst bubbles in the concentrate. The cumulative air recovery function is defined as the integral of a specific air recovery function, $f'_{AR}(x)$ over x from 0 to x. The physical meaning of the specific air recovery is the probability of a bubble entering at position x that is recovered as unburst bubble at the discharging lip. Table 1 gives six different expressions for $f_{AR}(x)$ and the corresponding $f'_{AR}(x)$.

It was reported by Leiva (2011) that on the basis of the experimental work for a two-phase foam system, the cumulative air recovery function follows an 'S-Shaped' curve. In the present work, however, six different $f_{AR}(x)$ functions were tested (see Table 1). These cumulative air recovery function have two constraints: $f_{AR}(0) = 0$ and $f_{AR}(1) = \alpha$. This means that at the back wall of the cell ($x = 0$), the cumulative air recovery must be 0, and at the froth discharge lip ($x = 1$), it should be equal to the overall air recovery, α, which is measurable. The overall air

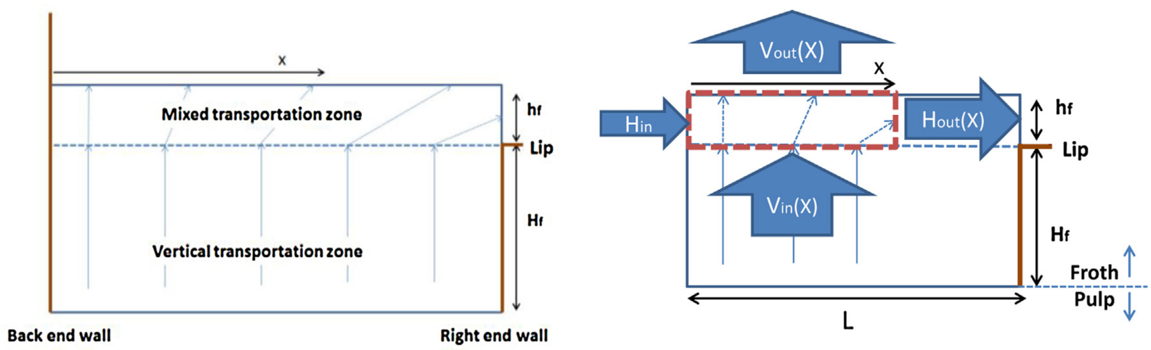

Fig. 1 – (L.H.S) Schematic drawing of the froth transportation zone. (R.H.S) Mass balance across the mixed transportation zone (Contreras et al., 2013).