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Real-time monitoring of entrainment using fundamental models and froth images

Khushaal Popli, Artin Afacan, Qi Liu, Vinay Prasad*

Department of Chemical and Materials Engineering, University of Alberta, Edmonton, Alberta T6G3G6, Canada

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ABSTRACT

In this study, entrainment monitoring algorithms were developed, trained and implemented on the batch flotation of three synthetic mixtures of galena and quartz with different particle size ranges for the quartz mineral. An online image-based soft sensor framework was developed to estimate product grade and recovery using support vector regression. A dynamic fundamental model was developed with emphasis on the entrainment and drainage sub-processes. The model was reconciled with online soft sensor measurements and was updated in real-time by estimating the states and parameters using an extended Kalman filter. Along with the online measurements of quartz entrainment recovery, measurements of entrainment and the true flotation contribution for galena particles were obtained in real-time. The proposed monitoring framework was shown to be effective in monitoring entrainment and the grade and recovery of the desired minerals.

1. Introduction

The most commonly used mineral separation technique in mineral processing, froth flotation, is based on the principle of selective attachment of mineral particles to gas bubbles. In the majority of flotation processes, the desired mineral is induced with surface hydrophobicity to increase the propensity to attach to gas bubbles, in order to achieve separation from other non-desired (gangue) minerals. With the depletion of good quality (i.e., easily separable) ores, efforts are being made to achieve the desired separation from low quality (i.e. difficult to separate) ores. To process low quality ores, minerals liberation is achieved through fine grinding. However, fine particle flotation causes two major problems: reduction in the attachment of hydrophobic value mineral particles, leading to low recovery, and an increase in the quantity of hydrophilic particles in the concentrate through entrainment, leading to low grade.

Entrainment is a phenomenon wherein the solid particles suspended in the pulp enter the froth phase and the concentrate stream purely by mechanical or hydraulic means rather than by genuine flotation. It is considered a two-step process: upward transfer of particles from the top of the pulp phase to the froth phase, and transfer of these particles from froth phase to the concentrate (Seaman et al., 2006; Wang, 2016; Gorain et al., 1998). The literature reports three ways suspended particles can be entrained and transferred to the froth phase (Wang, 2016; Smith and Warren, 1989; Gong et al., 2011; Gaudin, 1957; Moys, 1978; Hemmings, 1981; Bascur and Herbst, 1982; Yianatos et al., 1988):

- **Bubble swarm theory:** Bubbles are crowded just below the pulp-froth interface and the trapped water along with the suspended particles flows downwards. Buoyancy from the bubble swarm pushes some of the water and suspended particles over the interface (Smith and Warren, 1989; Gong et al., 2011).
- **Boundary layer theory:** The water layer surrounding the bubbles is used to carry the suspended particles to the froth phase (Gaudin, 1957; Moys, 1978; Hemmings, 1981; Bascur and Herbst, 1982; Wang, 2016).
- **Bubble wake theory:** The wake generated by the flowing bubbles is used to transfer the suspended particles to the froth phase (Yianatos et al., 1988; Wang, 2016).

Bubble swarm theory is generally accepted as the dominant mechanism for mechanical entrainment of suspended particles (Wang, 2016; Gong et al., 2011). Entrained particles, along with the particles detached in the froth phase, can be transferred back to the pulp phase by drainage (Cutting et al., 1986). Plateau borders are formed by the assembly of the water layer surrounding the bubble in the froth zone as shown in Fig. 1. They provide passage for the drainage of the water and entrained solids, and encourage their settling (Neethling and Cilliers, 2002a).

Entrainment to the concentrate stream is the net upward motion of the suspended particles. The entrained particles are part of the water in the plateau border. Many researchers have studied the relationship between water recovery and entrainment recovery (Trahar, 1981;

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* Corresponding author.
E-mail address: vprasad@ualberta.ca (V. Prasad).

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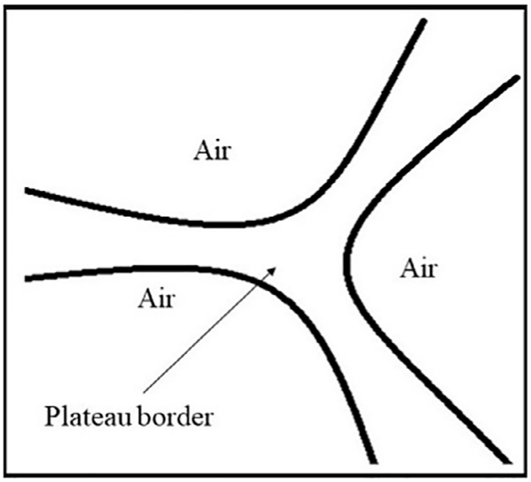

Fig. 1. Plateau border.

Engelbrecht and Woodburn, 1975; Hemmings, 1981; Lynch, 1981; Johnson, 2005; Laplante et al., 1989). Most of the entrained minerals follow a linear relationship with entrained recovery and water recovery, and the slope is approximated as the degree of entrainment (Wang, 2016; Trahar, 1981; Zheng et al., 2006; Warren, 1985; Jowett, 1966). The entrainment is dependent on various feed parameters such as particle size (Wang, 2016; Smith and Warren, 1989; Lynch, 1981) and particle density (Wang, 2016; Johnson, 2005; Maachar and Dobby, 1992), and operational parameters such as pulp density (Zheng et al., 2006; Johnson, 2005), impeller speed (Wang, 2016; Akdemir and Sonmez, 2003), and gas flow rate (Wang, 2016; Zheng et al., 2006).

Entrainment is non-selective and affects both hydrophilic and hydrophobic particles. The presence of hydrophilic particles in the froth phase reduces the grade of the desired minerals and reduces the efficiency of the flotation process for the separation of fine ground ore. Several methods have been suggested to reduce entrainment in froth flotation. These methods can be grouped into the following categories: reducing the water recovery, increasing the drainage (Gong et al., 2011), and direct reduction in the particle suspension by selective flocculation (Gong et al., 2011, 2010; Liu et al., 2006). A washwater stream has been introduced in flotation to wash the froth and increase the drainage of particles by providing counter-current flow (Gong et al., 2011; Mulleneers et al., 2002).

To improve the product grade, entrainment needs to be minimized, monitored, and controlled. Entrainment needs to be measured in real time for effective monitoring and control. Since a reduction in the overall entrainment also reduces the amount of hydrophobic (desired) minerals (the entrainment contribution), entrainment needs to be measured for hydrophilic and hydrophobic minerals individually. Entrainment of hydrophilic minerals is usually measured off-line by timed weight measurements (with a long sampling time)followed by X-ray fluorescence (XRF) measurements (which also have longer sampling times). It is difficult to measure the entrainment contribution of the hydrophobic minerals. Recovery obtained by various methods provides the sum of true flotation and mechanical entrainment contributions. Three common methods are proposed in the literature (Trahar, 1981; Warren, 1985; Ross, 1988). Trahar (1981) suggested that two flotation tests, one in the presence of collector and frother (true flotation and entrainment), and the other in the presence of only the frother (entrainment), can be used to quantify entrainment. Differences in solid recovery between the two tests can be attributed to the true flotation, through which entrainment can be quantified. This method is not suitable for naturally hydrophobic minerals that have the capability of attachment even in the absence of a collector, or even in cases where the frother demonstrates collecting capabilities. Also, different reagents in both tests would influence the froth structure and further affect the drainage and entrainment in both runs (Wang, 2016; Ross, 1989). Warren (1985) explored the linear relationship between solids recovery and the water recovery as described in the following equation:

$$R(t) = R_f(t) + KR_w(t) \tag{1}$$

where R(t), R_f(t), K and R_w(t) represent the overall recovery at time t, true flotation recovery at time t, degree of entrainment, and water recovery at time t, respectively. Recovery due to entrainment is represented as KR_w(t) at time t. Various experiments need to be conducted at different water recoveries obtained by varying the froth height, froth, pulp height, or the rate of froth removal (Warren, 1985; Pita, 2015). The true flotation recovery (R_f(t)) and the degree of entrainment (K) can be calculated using a linear regression relation between the overall mineral recovery and water recovery. However, varying the froth height, pulp height or the rate of froth removal also disturbs the froth structure and consequently the drainage and entrainment rates. Hence, this method does not give an accurate measurements of the entrainment contribution. Also, it should be noted that the degree of entrainment changes with time and its variation is not considered in this method. Along with these drawbacks, this method requires numerous test runs, making it time consuming and economically infeasible. Another method, based on a single flotation test, was proposed by Ross (Ross, 1988). It is based on the calculation of two timed functions X(t) and Y (t):

$$X(t) = \frac{E(t)\cdot C_w(t)}{W(t)\cdot C_m(t)} \tag{2}$$

$$Y(t) = \frac{R(t)\cdot C_w(t)}{W(t)\cdot C_m(t)} \tag{3}$$

where E(t), R(t), W(t) C_w(t), and C_m(t) represent the total mass of entrained solids at time t, the total mass of recovered solids (true flotation and entrained) at time t, the total mass of water recovered at time t, the concentration of water in the pulp at time (t), and the concentration of solids in the pulp at time t, respectively. This method is based on three assumptions: a) the recovery at the end ($t = \infty$) of batch flotation is solely due to entrainment, b) the timed function X(t) decreases linearly with flotation time, and c) the pulp is homogeneous. At $t = \infty$, X(t) can be approximated by using the assumption X(t) = Y(t), and Y(t) is calculated based on the total mass recovered. Based on the X(t) values towards the end of the flotation run, the X(t) line is extrapolated towards time t = 0 such that it increases linearly while moving from time $t = \infty$ to t = 0. It is critical to run the batch process until the optimum time where all the solids recovered are due to entrainment (Ross, 1988; Pita, 2015). Using the above simplification, the entrained mass E(t) can be calculated by measuring the mass of water recovered (M(t)) and the concentration of the specific mineral in the pulp (C_m(t)):

$$E(t) = M(t)C_m \tag{4}$$

This method provides inaccurate results for hydrophobic species, as their concentration in the pulp changes due to both true flotation and entrainment. In other words, hydrophobic minerals in the pulp are available for attachment to the bubbles as well as entrainment. Furthermore, most of these methods require a number of batch flotation tests to be completed before calculating the contribution from entrainment. In addition to the potential inaccuracies, these methods cannot be used to obtain real-time measurement of the entrainment contribution for the minerals floated. Hence, there is a critical need for a method to measure the entrainment contribution in real-time.

Several authors have proposed models for entrainment recovery. These models can be classified as empirical (Maachar and Dobby, 1992; Ross, 1989; Bisshop and White, 1976; Savassi et al., 1998; Yianatos and