International Journal of Mineral Processing 124 (2013) 102–108

Contents lists available at ScienceDirect

International Journal of Mineral Processing

journal homepage: www.elsevier.com/locate/ijminpro

A modeling approach using back-calculated induction times to predict recoveries in flotation ☆

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ARTICLE INFO

Article history:
Received 20 July 2012
Received in revised form 4 April 2013
Accepted 20 April 2013
Available online 7 May 2013

Keywords:
Flotation modeling
Flotation efficiency
Induction time
Liberation
Floatability

ABSTRACT

The current modeling flotation approach of the Julius Kruttschnitt Mineral Research Centre (JKMRC) predicts recoveries in a flotation circuit using a lumped parameter called the floatability of mineral particles (P) which has no direct physical meaning and is assumed to be conserved in flotation circuits in the absence of regrinding or change in chemical environment. In this paper, the original definition of P as the efficiency of collection was resurrected. Fundamental models of particle collection by bubbles were applied to an industrial data set from a down-the-bank flotation survey of the first four cells of the galena rougher circuit at BHP Billiton's Cannington operation in Australia. The floatability of mineral particles P was no longer treated as a lumped parameter but described by the physical measurable inputs of the models. Induction time as a model parameter was back-calculated from knowledge of the experimental data and application of the collection model. The assumption that the induction time of a size-by-liberation class at fixed chemistry was conserved allowed prediction of galena recoveries in the circuit. An extensive error analysis was conducted on the new modeling approach and it was found to be very sensitive to the value of the bubble rise velocity. Finally, since the variation in the key flotation variables down the bank at the BHP Billiton Cannington's lead rougher circuit was not significant, the two approaches predicted similar flotation kinetics down the bank.

1. Introduction

Researchers have been trying to model flotation for two reasons; to understand the theory behind the flotation process and to use the model for plant design and simulation. It is not a trivial task to predict the behavior of a flotation circuit when changes are made. The mineralogy could be complex with two or more valuable mineral species needing to be recovered. Regrinding and reagent addition are often found in flotation circuits. The complexity of the circuit makes it impossible to predict its final recovery and grade without modeling the process.

The P9 flotation model has successfully been used to model industrial circuits. It uses the following equation (Savassi, 1998):

$$R = \frac{k_c \tau R_f (1-R_w) + ENT \cdot R_w}{\left(1 + k_c \tau R_f\right)(1-R_w) + ENT \cdot R_w} \quad (1)$$

where R is the recovery of the mineral of interest, k_c is the flotation rate constant in the pulp zone, τ is the residence time, R_f is the froth recovery, R_w is water recovery and is defined as the ratio of mass of water in concentrate to the mass of water in feed and ENT is the degree of entrainment. The relationship between k_c the pulp zone flotation rate constant and S_b the bubble surface area flux is $k_c = PS_b$ (Gorain, 1998) where P is the floatability of mineral particles. The model includes the contribution of true flotation and entrainment on overall recovery.

The methods for obtaining parameters other than P in Eq. (1) are through cell characterization measurements and calculations resulting from a mass balance of a flotation survey. The bubble surface area flux S_b can be obtained by measuring the bubble size d_b and superficial gas velocity J_g. Froth recovery R_f is obtained through measuring bubble load and the results of the survey mass balance. The cell residence time τ can be calculated through the survey mass balance, air holdup ε_g which can be measured and knowledge of the cell volume. Entrainment ENT, water recovery R_w and the recovery of the mineral of interest R can be calculated from the results of the mass balance survey.

Currently, values of P for industrial circuits or pilot plants are obtained through the floatability component modeling (FCM) approach (Harris, 1998; Runge et al., 1997). A flotation survey is conducted in conjunction with batch flotation tests. Discrete values of P_i and the mass proportions (m_i) of component i are calculated using non-linear regression techniques. If there are no changes to

☆ Parts of the paper were submitted for the XXV International Mineral Processing Congress, Brisbane.

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http://dx.doi.org/10.1016/j.minpro.2013.04.013

the ore feed stream, then as a first approximation to the problem, P_i is a lumped parameter that is assumed to be conserved throughout a circuit. When flotation conditions change that are not ore dependent or chemical dependent, that *same* number P_i is used to predict recoveries and grades.

Typically, the approach sets the components as rate related, but the components can also be related to physical properties of particles. Gorain et al. (2000) successfully used FCM to predict recoveries in roughers and scavengers by assuming that the P value of a size-by-liberation class did not change throughout the circuit. To differentiate this between traditional floatability component modeling where the components are rate related (non-floating, slow and fast floating), this type of property-based floatability component modeling will be termed modified floatability component modeling (MFCM).

While floatability component modeling is a useful tool, there are inherent problems in using it for predicting changes in floatability. Firstly, at parts in the process that change the properties of the particles, such as a regrind mill or at a reagent addition point, the floatability component modeling approach cannot predict the change in floatability of mineral particles. At best, it can only record the difference in P through deriving the values before and after that process point. Secondly, even though P has been termed the floatability of mineral particles in an ore, it must be understood that it is not an inherent property of the ore. It is a flotation response dependent on the cell operating conditions (including chemical environment), as well as the ore characteristics. If the conditions of the plant change too far from the conditions of the survey that were initially used to obtain P_i, the values will no longer be correct and they have to be re-derived.

Therefore, it is desired to find a modeling approach that can accommodate changes such as feed head grades, or particle size at fixed chemistry. By recognizing that P was originally defined as the efficiency of flotation, it widened the search of the literature to include fundamental models that describe the microkinetics of flotation at the particle-bubble level. The modeling of the microkinetics of flotation gives (Finch and Dobby, 1990; Gorain, 1998; Jameson et al., 1977; Nguyen and Schulze, 2004):

$$P = \frac{E_c E_a E_s}{4} \tag{2}$$

where E_c, E_a and E_s are the efficiencies of bubble–particle collision, attachment and stability in the pulp zone. The efficiencies can be affected by particle density, pulp viscosity, induction time, particle size, shape and composition, gas holdup, bubble size, turbulence, bubble velocity, particle velocity, etc. If any of the model inputs change then the efficiency of flotation changes and so in theory, P should change depending on the variation of the model inputs. When this is taken into consideration, it is not difficult to understand why recoveries may not be adequately predicted by a lumped parameter P in the event of some process changes.

The models that were for the microkinetics of flotation (Nguyen and Schulze, 2004) could meet the criterion that the variables have physical meaning and thus were amenable to measurement. There was only one variable which could not be measured in a flotation cell — the induction time of a particle, i.e., the time required for thinning and rupture of the water film between particle and bubble. If the induction time is less than the time of contact between the particle and the bubble (i.e., sliding time), then attachment will occur.

The fact that induction time appears in the efficiency of the attachment model as an explicit variable presents both difficulties and advantages. The advantage of induction time is that it is a variable related to surface chemistry and so it has the potential to provide a link with future research related to changing chemical environment. The difficulty with induction time is that, presently, it can only be measured in idealized systems and not in industrial plants or under realistic flotation conditions.

This paper presents a modeling approach validation study conducted using plant survey data and the microkinetics flotation models which allow one to back-calculate induction time on a size-by-liberation basis for the first few flotation cells of the bank and then to apply the induction time to predict recoveries in the remaining cell using Eqs. (1) and (2). In doing so, it is assumed that, in place of the lumped parameter P, the back-calculated induction time of a size-by-liberation class is conserved down the bank. The methodology for obtaining induction time is similar to that used by Savassi and Dobby (2006) although in that paper, the induction time was an interim step in obtaining the hydrophobicity index. The other difference was that Savassi and Dobby (2006) used simplified equations of Dobby and Finch (1987) for the efficiency of collision and attachment with bubbles having an immobile (rigid) surface. This paper uses equations from Nguyen's microkinetic models of flotation which consider air bubbles with a mobile surface, finite gas holdup and intermediate Reynolds number (Nguyen and Schulze, 2004).

The objective of the paper is to answer the question of whether the assumption of a conserved back-calculated induction time (BCIT) for a size-by-liberation class is valid by comparing model values predicted by the BCIT approach with experimental values found during the survey. The study also aims to establish whether or not separating the lumped parameter P further and describing it with fundamental models gives recovery predictions that are closer than those predicted by the modified floatability component modeling (MFCM).

2. Materials and methodology

2.1. Microkinetics flotation models with gas holdup

There are a number of excellent reviews on the models for the microkinetics of flotation (Dai et al., 2000; Nguyen and Schulze, 2004; Yoon, 2000). The reviews show that the majority of the models consider idealized interactions between a single particle and a single bubble with a rigid (solid-like) surface. However, industrial flotation is accomplished by many swarms of bubbles and particles and thus the motion of an air bubble and a particle in a flotation cell is firstly affected by the presence of other bubbles and particles. The gas and solid holdups, and the interactions between neighboring bubbles and particles tend to straighten the liquid streamlines around a bubble and a particle, and significantly affect the microkinetics of flotation (Nguyen and Schulze, 2004). The holdup effect on the microkinetics of flotation was first described by Finch and Dobby (1990).

The holdup effect on the flotation microkinetics with mobile bubble surfaces was later considered in predicting both collision and attachment efficiencies by Nguyen (1999) which are described as follows (Nguyen and Schulze, 2004):

$$E_c = f(R)\frac{(X+C)\sin^2\theta_c - C_1X^2\frac{\cos^3\theta_c - 3\cos\theta_c + 2}{3}}{1+v_s} \tag{3}$$

$$E_a = \frac{(X+C)\sin^2\theta_n - \frac{1}{3}C_1X^2\left(\cos^3\theta_n - 3\cos\theta_n + 2\right)}{(X+C)\sin^2\theta_c - \frac{1}{3}C_1X^2\left(\cos^3\theta_c - 3\cos\theta_c + 2\right)} \tag{4}$$

where $f(R) = R - R^2$ is a function of the ratio of particle to bubble radius (called the interception number, $R = R_p / R_b$). The key model parameter, X, arising from the numerical solutions of the Navier–Stokes equations (Nguyen, 1999) is a function of the bubble Reynolds number, Re, and the gas holdup, ε_g, which is described as

$$X = 1 + \frac{0.0637\mathrm{Re}}{1 + 0.0438\mathrm{Re}^{0.976}} + \left(5.274 - 0.588\mathrm{Re}^{0.23}\right)\varepsilon_g^{0.711}. \tag{5}$$

The bubble Reynolds number is defined as $\mathrm{Re} = 2UR_b\delta/\mu$, where δ is the pulp density, and μ is the pulp viscosity. The bubble velocity, U, was obtained by following the method shown in the paper by