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The implications of the froth recovery at the laboratory scale

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ABSTRACT

This paper presents a critical review of the role of froth recovery in laboratory flotation kinetics tests. By conducting tests in the standard lab equipment (the Denver cell), it is demonstrated that, for typical scraping rates, the froth recovery is significantly lower than the 100% that is commonly assumed when interpreting lab kinetics data. Furthermore, it is shown that the curve of overall rate constant versus froth residence time, as defined by the scraping rate, is not linear, but increases quickly at faster scraping rates. These findings have important implications for scale-up. For one, differences in froth recoveries at the lab scale can lead to significant error in the modeled plant recoveries. For two, they undermine a key assumption used to derive and validate the linear relationship between collection rate constant and bubble surface area flux. This casts doubt on the assertion that it is only the collection rate—rather than the froth recovery, interface recovery, or some combination thereof—that is responsible for the observed collinearity between the bubble surface area flux and the overall rate constant.

1. Background

The flotation kinetics test remains the workhorse of flotation circuit design and scale-up. The test is conducted by putting a known mass of sample in a laboratory flotation cell with water and reagents and adding air and agitation for fixed time intervals, over which concentrate samples are collected. A curve of cumulative metal recovery as a function of time is determined from the resulting feed, concentrate and tails assays.

The curve of cumulative metal recovery versus time is usually converted into the equivalent curve or curves of mineral recovery versus time, as flotation rate parameters apply to minerals, not elements (this because there can be several minerals with the same element present). Once the cumulative recovery time profile is derived, usually from a combination of quantitative mineralogical and stoichiometric information, the kinetics are calculated for each mineral using curve fitting techniques.

The most common rate equation for modeling batch tests is the pseudo-first order plug flow rate equation, which expresses cumulative recovery as a function of flotation time (Garcia-Zuñiga, 1935),

$$R = (1 - e^{-kt}) \qquad (1)$$

where k is the overall pseudo-first order flotation rate constant with respect to time (1/min). The froth recovery, R_f, in the batch test is defined as the ratio of the overall rate constant to the collection zone rate constant, k_c (Finch and Dobby, 1990; Vera et al. 1999):

$$R_f = \frac{k}{k_c} \qquad (2)$$

Substituting Eq. (2) into Eq. (1) and adding a term, $R_{\max}$, to account for mineral liberation and locking effects, yields:

$$R = (1 - e^{-k_c R_f t}) R_{\max} \qquad (3)$$

For continuously fed stirred tank reactors (CSTR), the recovery of mineral into the concentrate can be represented schematically by Fig. 1, where R_c is the recovery of particles in the collection zone.

Mathematically, the recovery by flotation, R_{flot}, is expressed as (Finch and Dobby, 1990):

$$R_{\text{flot}} = \frac{R_c R_f R_{\max}}{R_c R_f + 1 - R_c} \qquad (4)$$

1.1. Discussion of the collection zone

One of the main difficulties with the above equations is that the froth recovery term, R_f, always appears as a product with either the collection zone rate constant, k_c, or the collection zone recovery term, R_c. This presents a challenge when studying the response of R_c or R_f to changing system parameters. The problem has traditionally

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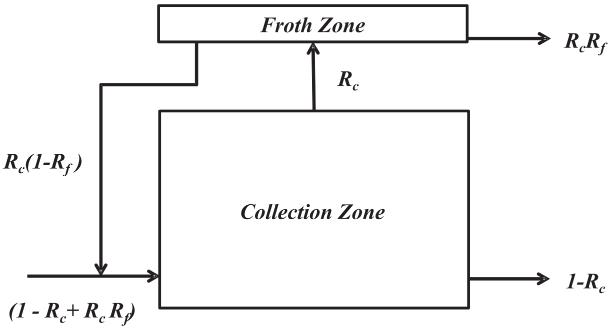

Fig. 1. Schematic representation of the compartmental model (Finch and Dobby, 1990).

been resolved by considering that under some conditions the froth recovery can be assumed to be 100%, in which case Eq. (2) would dictate that the overall rate constant is equal to the collection zone rate constant. This key assumption underlies the body of work deriving (Gorain et al., 1998a) and validating the linear relationship between bubble surface area flux (S_b) and collection zone rate constant. More specifically, in order to suggest that that S_b drives collection rate, researchers used the series of tests performed at a shallow froth height to justify the assumption that $R_f = 100\%$ and thereby derive Eq. (5) (Gorain et al., 1998a).

$$k = k_c R_f = P S_b R_f \qquad (5)$$

In an earlier work, Jameson et al. (1977) reported on the physical significant of Eq. (5). By defining the collection efficiency, E_c, as the fraction of particles removed by a bubble as it rises in a tube (i.e. the collision efficiency times the attachment efficiency), the removal rate of floatable particles per unit time is defined as (Jameson et al., 1977):

$$\frac{dN_p}{dt} = -\left(\frac{3QE_c h}{2d_b V_c}\right) N_p \qquad (6)$$

where N_p is the number of floatable particles, Q is the air flow rate, V_c and h are the cell volume and height, and d_b is the bubble diameter. Eq. (6) can be simplified by substituting the definitions for J_g and S_b:

$$J_g = \frac{Qh}{V_c} \qquad (7)$$

$$S_b = \frac{6J_g}{d_b} \qquad (8)$$

Solving the differential equation yields the following expression for k:

$$k = \frac{E_c S_b}{4} \qquad (9)$$

Eq. (9) is often cited as the physical basis for Eq. (5) (*sans* froth term), and the idea has been supported by both experimental and theoretical works. For example, Deglon et al. (1999) performed bubble population balance simulations using attachment and detachment kinetics measured for quartz particles. The simulation results support the notion of a linear relationship between k and S_b. But because in this study the attachment and detachment rates were derived under ideal lab conditions and assumptions that considered no froth effects, it is not known whether the detachment rate of particles was caused by detachment occurring in the froth or detachment occurring in the pulp. For this reason, the work only validates that the overall rate constant is linear with bubble surface area flux; it does not lend any additional support to Eq. (5) or Eq. (9).

In another work, Hernandez-Aguilar et al. (2004) studied the relationship between collection rate constant and bubble surface area flux at the micro scale and found that a linear relationship does indeed exist. However, their method only employed superficial air rates between 0.24 cm/s and 0.49 cm/s, and still required a small (0.5 cm) froth to improve the stability. Furthermore, the rate constants were calculated by assuming 100% froth recovery, so there is no way to conclusively show that the S_b was driving the collection rate rather than the froth recovery, interface recovery, or some combination of the three.

The above discussion serves to illustrate the challenges that arise from the adoption of a dual compartment flotation model. Simply stated, *it is difficult to judge the effect of a change in a system parameter on one compartment (the collection zone) without adequately characterizing the other compartment (the froth zone)*. To illustrate, Gorain et al. (1998b) employed the same data set used to propose Eq. (5) to show that the froth recovery can be expressed an exponential function of the froth residence time, calculated by dividing the froth height by the superficial gas velocity (J_g) and normalizing for cell geometry. Because J_g is directly proportional to S_b (Eq. (8)), these findings suggest that the S_b will also have a direct impact on froth recovery. The relationship between S_b and R_f has also been noted by Hadler (2006), Alexander (2006), and Hadler and Cilliers (2009).

1.2. Discussion of the froth zone

Some researchers (Vera et al., 1999; Vera et al., 2002; Alexander et al., 2003) have tried to account for the froth recovery by measuring the overall flotation rate constant at different froth heights and linearly extrapolating to zero froth height. While this method is an improvement over the previous methods of simply assuming 100% froth recovery, it is still not perfect because it assumes that the curve of R_f versus froth height is linear. The linearity assumption is supported (somewhat) by the work of Feteris et al. (1987), who studied laboratory scale batch flotation tests at froth heights ranging from 1.5 cm to 4.2 cm. They found a linear relationship between overall flotation rate and froth depth. Unfortunately, in that work the authors report neither the froth scraping rate nor the water recovery (to approximate the scraping rate from empirical data), so we can't determine the mean froth residence time for the various froth depths tested. As we shall see below, if the tests were performed for industry standard scraping rates of one scrape per 10 s or longer, then the resulting data would indeed correspond to the linear part of the froth recovery versus scraping rate curve, although this does not necessarily validate the linear extrapolation procedure proposed by Vera et al. (1999) and others.

Seaman et al. (2004) studied froth recoveries using bubble load measurement methods and obtained froth recovery values significantly lower than those estimated using the variable froth depth approach. They also report evidence of selective mineral recovery across the froth zone, and attribute both observations to the detachment of particles as they reach the pulp/froth interface, which, if correct, would invalidate the linear extrapolation approach described above. Nevertheless, despite the low froth recovery values and possible interface effects, the froth recovery was still approximately linear with froth depth for the range of froth height studied.

In another approach, Alexander (2006) used the froth mass balance method to calculate froth recoveries in industrial cells and compared the results to those predicted from the linear extrapolation approach. At one of the plants studied, permission was obtained to operate a large cell at shallow froth heights (7–20 cm). The resulting data show that the rate constants for all minerals start to increase very quickly – by as much as an order