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Modelling flotation with a flexible approach – Integrating different models to the compartment model

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ABSTRACT

In this work, a comprehensive model structure for froth flotation is developed by linking the compartment model (Savassi, 2005) to a set of phenomenological models describing the froth recovery, the water recovery and the entrainment factor. This model structure is successfully calibrated against experimental data from a pilot plant campaign with a copper ore.

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1. Introduction

The compartment model (Savassi, 2005) accounts for the simultaneous contribution of true flotation and entrainment to the overall recovery in a conventional flotation cell. The total volume of the cell is divided into three compartments: pulp collection zone, pulp quiescent zone and froth region, with the mechanisms being modelled as occurring at the same time but originating at different places: true flotation from the collection zone and entrainment from the quiescent one. The model is obtained by solving a set of equations describing the mass transfer of attached and suspended particles between adjacent compartments:

$$R = \frac{k_{cz} \cdot \tau_{cz} \cdot R_f \cdot (1 - R_w) + \mathrm{ENT} \cdot R_w}{(1 + k_{cz} \cdot \tau_{cz} \cdot R_f) \cdot (1 - R_w) + \mathrm{ENT} \cdot R_w} \tag{1}$$

where k_{cz} = flotation rate exclusive for the collection zone, τ_{cz} = residence time in the collection zone, R_f = froth recovery of attached particles, R_w = water recovery from the feed to the concentrate streams and ENT = degree of entrainment.

The compartment model allows the intricate nature of the mass conservation of solids and water in a flotation cell to be reduced to one single equation, overcoming the need of numerical methods for simulation purposes. Savassi (2005) demonstrated that the simplifications necessary for the development have no impact on model predictive power, as compared to using a more detailed description of the pulp hydrodynamics. Model calibration is based upon batch testwork along with the assays and solids percentages of different streams of the flotation system being investigated. No special measurements are required.

Other advantages of using the compartment model are:

- The variables of the general equation – especially the froth recovery of attached particles (R_f), the water recovery from the feed to the concentrate streams (R_w) and the entrainment factor (ENT) – may be modelled separately in higher or lower details, relating them to specific flotation conditions. More than one model can be evaluated for each of these variables and the most suitable may be adopted for the studied process, which brings flexibility to the structure.
- Since the pulp and froth phases are taken as separate compartments, the flotation phenomena can be better represented in each phase.
- The model can be applied to the floated mineral in the bulk ore, to mineral per particle size classes, or to mineral per size and liberation classes. Flotation parameters may be attributed to each class. As a result, the model is suitable for integration between flotation and grinding, since liberation and particle size classes can be directly linked to their effect in the process through the associated flotation parameters.

In this work, the compartment model was used together with a number of specific phenomenological models accounting for the sub-processes taking place in a conventional flotation cell. Only

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entrainment data will be evaluated for gangue and per particle size. Future work will evaluate the application of this model per size-liberation classes.

2. Specific models

2.1. Residence time in froth and air retention time – τ

Residence time in froth is a key parameter in froth modelling using kinetic models. There are different ways of estimating this time, which can be either based on the pulp or the air in the froth, as well as the pulp or air flowrates. Besides, the calculation can be made with the linear velocity or with volumetric flows and, for industrial cells, the estimate can also include vertical and horizontal froth transportation components, generating a froth residence time distribution (Zheng et al., 2004).

In this work, flotation was performed in a Mini Pilot Plant, in continuous circuit but with laboratory scale type cells. Besides, froth was restricted to an area where the continuous movement of froth scrapper predominantly constrained the froth movement to the vertical component. Then, residence time was estimated through the mean value, defined in two different ways, according to the froth model or entrainment model that demanded this estimate.

For the entrainment model of Bisshop and White, froth residence time (τ_{FR}) was calculated by the liquid volume in froth divided by the pulp flow rate of the concentrate, as shown in Eq. (2).

$$\tau_{FR} = \frac{V_f(1-\varepsilon_{gf})}{Q_{con}} \tag{2}$$

where V_f is the total froth volume in the flotation cell, ε_{gf} is the air hold up in the froth volume and Q_{con} is the volumetric concentrate flow rate into the froth launder.

Air retention time in froth (τ_f) is another way of expressing time for froth kinetic models. For the model of Savassi et al. (1998), it is defined by Eq. (3):

$$\tau_f = \frac{V_f}{Q_A} \tag{3}$$

where V_f is the total froth volume in the flotation cell and Q_A is the volumetric air flow rate into the froth launder.

2.2. Entrainment – ENT

Conceptually, the term entrainment refers to the main mechanism for the recovery of fully liberated gangue particles which are dispersed in a pulp. Among the theories that explain this mechanism, Smith and Warren (1989) suggested that water and suspended particles are mechanically pushed up into the froth region by ascending swarms of bubbles. The phenomenon is non-selective and is predominantly related to the pulp that remains among the bubbles from the pulp-froth interface to the concentrate launder. Therefore, the net flow of entrained particles to the concentrate results from two opposing flows:

- upward transport of water and suspended particles through the froth and
- drainage of entrained material down towards the pulp-froth interface.

These phenomena are typically represented by the recovery of free gangue and the recovery of water.

The recovery of free gangue is defined as the ratio between the amount of free gangue that reports to the concentrate and the amount of free gangue in the feed.

$$R_g = \frac{\text{free gangue in the concentrate}}{\text{free gangue in the feed}} \tag{4}$$

It has been demonstrated that there is a strong correlation between the water and free gangue recoveries (Smith and Warren, 1989; Savassi et al., 1998; Neethling and Cilliers, 2002). For fine particles, this relation tends to be linear. Since coarse particles are not significantly recovered by entrainment, the proportionality tends to be true for the overall recovery of free gangue within a reasonable range.

$$R_g \propto R_w \tag{5}$$

Then, in several studies and in this work, entrainment can be mathematically defined as the factor that relates R_g to R_w.

$$R_g = \text{ENT} \cdot R_w \tag{6}$$

Entrainment depends on pulp viscosity, solids percentage, frother dosage, air flowrate and particle size. Several models were proposed for mechanical entrainment, both of empirical aspect (Jonhson et al., 1974; Bisshop and White, 1976; Kirjavainen, 1992; Savassi et al., 1998; Yianatos and Contreras, 2010) and of fundamental nature (Moys, 1978; Neethling and Cilliers, 2002, 2009). Among the empirical models, the entrainment factor has been predominantly used to evaluate the effect of drainage on particles of different sizes. Within this approach, the model developed by Bisshop and White (1976), the model of Savassi et al. (1998) and, more recently, the model of Yianatos and Contreras (2010) can be highlighted.

Typically, the entrainment factor presents a strong decay with the increase in particle size, as shown in Fig. 1.

The empirical model proposed by Bisshop and White to represent this curve can be described according to Eqs. (7)–(9):

$$\text{ENT} = \frac{1+\alpha\cdot\tau_{FR}}{1+\epsilon_i\cdot\tau_{FR}} \tag{7}$$

$$\alpha = k_1\cdot(\rho_m - \rho_p) \tag{8}$$

$$\epsilon_i = \alpha\cdot\exp(k_2\cdot d_i) \tag{9}$$

where α and ϵ are the water and the entrained particle models, respectively, τ_{FR} is the froth residence time, which is estimated from the liquid volume in the froth divided by the concentrate flow rate, as in Eq. (2), ρ_m and ρ_p are the density of mineral particles and pulp, d_i is the equivalent diameter of the entrained particles and k_1 and k_2 are constants.

The model of Savassi et al. corresponds to an empirical partition curve which describes the effect of the diameter, d_i, of particles of a

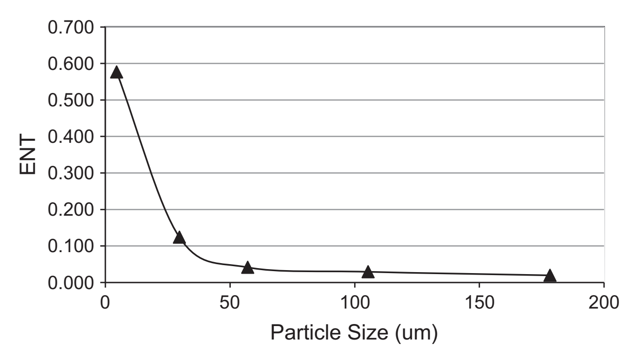

Fig. 1. Example of the decay of entrainment with particle size.

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