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Influence of flotation cell hydrodynamics on the flotation kinetics and scale up, Part 2: Introducing turbulence parameters to improve predictions

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ABSTRACT

The AMIRA P9 model has floatability (P) as the ore property which is considered to remain constant in different flotation cell sizes under different hydrodynamic conditions. However, in this study increasing the power input increased the P value, especially in finer particle size classes (below 75 μm). Acceptable explanations for the floatability variations, as a result of hydrodynamic condition variations in the flotation cells, have been sought by looking at the literature and the results obtained in this study were published in part one of this manuscript. To improve the accuracy of the AMIRA P9 flotation model in predicting flotation rate constant (k) and to improve the consistency of ore property, measurable and appropriate turbulence parameters were sought to be incorporated into the model. Therefore, two dimensionless turbulence parameters æ and EVF, derived from practical measurements, were formulated and introduced to the AMIRA P9 model. The modified ore floatability parameter, P″, was demonstrated to be a more consistent characterisation of the ore property than P and both the accuracy and precision of the k prediction improved for a variety of hydrodynamic conditions of flotation cells.

1. Introduction

The AMIRA P9 model has been applied in a number of flotation studies and has been successfully used to optimise several industrial flotation circuits (AMIRA P9 reports, 2000, 2004a,b). The model is explained in detail in part one of this paper. Other studies (Amini et al., 2009; Collins, 2007) showed that the ore property (P value) is not constant when scaling up from laboratory to pilot plant or industrial scales, and that the P value changes with varying hydrodynamic conditions in cells. It was shown in the first part of this manuscript that increasing impeller speed and turbulent kinetic energy dissipation rate (TKEDR) changed the P value, which is contrary to the proposed mechanism of Gorain (1997) and Gorain et al. (1998) who reported that impeller speed changed bubble surface area (S_b) which is a function of bubble size distribution, but not the P value in his experiments on industrial cells. This implies other factors such as impeller speed influence the P value in small scale flotation cells. Varying impellor speed is not a control variable available in industrial plant operation. It is however an important concept in relating laboratory flotation kinetic test data to industrial plant scale-up. As a result, a fitted scale-up number needs to be applied to the P value predicted by the AMIRA P9 model.

Hernandez-Aguilar (2011) and Hernandez-Aguilar et al. (2005) reported that the P value does not have a linear relationship with the flotation rate constant as claimed by Gorain (1997) and Gorain et al. (1998). The authors showed that incorporating a new bubble size factor into the model can improve the model predictions in column flotation. Their new model seems to work when the Sauter mean bubble diameter (d_{32}) is lower than 1.2 mm but Gorain's relationship is still valid in the column flotation cells where no agitation is required. The mean value of d_{32} in the mechanical flotation cells in the industry is equal to 1.7 mm (Schwarz and Alexander, 2006) showing that Hernandez-Aguilar (2011) is not valid for the mechanical cells. Moreover, the authors did not take into account the effect of bubble size distribution and bubble particle loading on froth stability and froth drop-back (Laskowski and Woodburn, 1998; Bulatovic, 2007) when the R_f was calculated in their studies. That is a crucial factor in the rate constant calculation in industrial test work. Putting the result of the studies together indicates experimental test work with minimum froth effect is required to analyse the relationship between flotation rate constant (k) and S_b in pulp zone.

In contrast, the fundamental flotation models discussed in part one already contain hydrodynamic factors such as energy

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Nomenclature

æ	dimensionless number that represent hydrodynamic condition of the cell
d_b	diameter of bubble (mm)
EVF	effective volume factor (dimensionless)
k	flotation rate constant (1/min)
P	floatability as defined in AMIRA P9 flotation model (dimensionless)
P′ and P″	floatability as defined in the modified P9 flotation model (dimensionless)
R_f	recovery of particles across the froth (%)
S_b	bubble surface area flux (1/s)
TKEDR	turbulent kinetic energy dissipation rate (m^3/s^2)
ν	kinematic viscosity (m^2/s)
ρ	density (m^3/kg)

dissipation rate, bubble size, viscosity, and number of bubbles. Application of several parameters makes the fundamental models sensitive to the majority of influential parameters in the flotation process. However, calculation or measurement of each parameter has an associated error and more parameters simply mean a bigger uncertainty in the calculated/predicted flotation rate constant. Also, some of the parameters in the fundamental models cannot be directly measured, which increases the uncertainties in calculation even more.

It was found that bubble size, energy dissipation rate and viscosity are the most important factors influencing bubble-particle collision rates (Schubert, 1999; Abrahamson, 1975). It was also assumed that the volume of the cell that contains higher TKEDR affects the flotation rate constant by increasing the overall collision rate in the cell (Savassi, 1998). Savassi (1998) divided the pulp in a flotation cell into two zones: (1) The "Collection" zone (near the impeller), which contains high turbulence intensity and where the majority of bubble particle attachment occurs and (2) The "Quiescent" zone (outside the impeller region), which contains very low turbulence intensity and where the interaction between bubbles and particles is very low. The existence of these zones was also observed by other researchers (Pyke, 2004; Newell and Grano, 2006, 2007) and is demonstrated in part two of this manuscript. The quiescent zone or disengagement zone indicates the zone that bubble-particle attachment or detachment rate is considerably lower compare to the high turbulent zone (Matis, 1995).

It was demonstrated in part one of this manuscript that it is possible to make appropriate measurements to characterise the hydrodynamic conditions of flotation cells of any size. Turbulent kinetic energy dissipation rate (TKEDR), bubble size, shear and viscosity are the key influential parameters in a flotation process which can be measured with practical methodologies and used for modelling purposes.

Introducing dimensionless turbulence parameters to the AMIRA P9 model (modified AMIRA P9 model) can reduce the error in calculating of ore property. Thus it enhances the flotation rate constant prediction for a variety of size and hydrodynamic conditions of flotation cells.

2. Development of dimensionless numbers

It was shown that the floatability (P value) is proportional to hydrodynamic conditions of a flotation cell (see part one). The hydrodynamic effect may be described using two expressions related to the pulp hydrodynamics (æ) and effective cell volume (EVF).

The fundamental flotation models indicated that the flotation rate constant is directly proportional to bubble-particle collision frequency, which is a function of kinematic viscosity (ν), turbulent kinetic energy dissipation rate (TKEDR), bubble diameter (d_b), density (ρ) and bubble surface area flux (S_b). These parameters have the dimensions of (L^2T^{-1}), (L^2T^{-3}), (L), (ML^{-3}) and (T^{-1}), respectively. Bubble surface area flux is already present in the AMIRA P9 model so the extension of the model could contain the other four parameters. Thus, a dimensionless number, which is called æ, can be written using d_b, TKEDR, ν and ρ:

$$æ = d_b.TKEDR^a \cdot \nu^b \cdot \rho^c \tag{1}$$

By introducing the dimensions we have

$$æ = L \cdot \left(\frac{L^2}{T^3}\right)^a \cdot \left(\frac{L^2}{T}\right)^b \cdot \left(\frac{M}{L^3}\right)^c \tag{2}$$

where a, b and c are the parameters which should be calculated by solving the equation for each fundamental quantity to eliminate the dimensions.

$$\text{For length (L)}: 1 + 2a + 2b - 3c = 0 \tag{3}$$

$$\text{For time (T)}: 3a + b = 0 \tag{4}$$

$$\text{For mass (M)}: c = 0 \tag{5}$$

Solving the Eqs. (3)–(5) returns values of a = 0.25, b = −0.75 and c = 0.

Therefore, æ can be written as

An expression to describe pulp hydrodynamic conditions incorporating pulp viscosity (ν), arithmetic mean bubble size (d_b) and the turbulent kinetic energy dissipation rate (TKEDR) has been developed and is shown as Eq. (6). The derivation of the equation was published in detail (Amini, 2013).

$$æ = \left(\frac{d_b \cdot TKEDR^{0.25}}{\nu^{0.75}}\right)^n \tag{6}$$

where n is estimated by the number of flotation tests over a range of operational conditions. It is suggested to conduct three lab scale flotation tests at three levels of impeller speed to fit n value where floatability remains constant for each floatability class (e.g. size by size P values) over the operational range.

When only æ is incorporated into AMIRA P9 model ore property (P′) can be estimated from this model. The P′ becomes more of an ore property compared to the P in the original AMIRA P9 model ($k = P \times S_b \times R_f$).

$$k = P' \times S_b \times æ \times R_f \tag{7}$$

From Savassi's assumption, it can be concluded that increasing the energy dissipation rate increases the collision frequency. Thus, increasing the energy dissipation rate increases the flotation rate constant, but only up to a point where detachment overrides the collision frequency effect, especially for coarse particles. Increasing the volume of the "high" turbulent zone (TKEDR > 0.1 m^2/s^3 in this study) increases the collision frequency in a flotation cell and the flotation rate constant increases. Therefore, the proportion of the cell volume, which contains a high-energy dissipation rate (here called the Effective Volume Factor or EVF), is introduced here: