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An attachment-detachment kinetic model for the effect of energy input on flotation

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ABSTRACT

This paper presents an attachment-detachment kinetic model for describing the effect of energy/power input on the flotation rate constant. The attachment-detachment kinetic model is developed and applied to the experimental data of Safari et al. (2016) to produce a data set of several thousand size-by-size attachment/detachment rate constants derived from 460 flotation tests. This data is used to derive empirical correlations for describing the relationship between the attachment/detachment rate constants and the particle size, particle density, bubble size, collector dosage and energy input. The attachment detachment model, used in conjunction with the empirical correlations for the rate constants, is able to predict the experimental data reasonably well in terms of both magnitude and trends. In addition, several exponents used in the empirical correlations for the rate constants are comparable to values found in the flotation literature.

1. Introduction

Froth flotation is a separation method used for the beneficiation of a considerable portion of the world's mineral ores. Researchers have for many decades attempted to model the flotation process in an effort to better understand and improve flotation performance (Gaudin, 1957; Bascur et al., 1983; Deng et al., 1996; Pyke et al., 2003; Bloom and Heindel, 2003; Dobby and Savassi, 2005; Sherrell and Yoon, 2005; Barnwal, 2006; Goel and Jameson, 2012; Karimi et al., 2014). In general, flotation models can be categorised into fundamental, kinetic, empirical and phenomenological models. Fundamental models incorporate physical understanding of the flotation micro-environment and are capable of predicting performance reasonably accurately. However, these model are generally complex, requiring fundamental parameters which are difficult to measure and implementation by computationally intensive simulations such as CFD or DEM. Kinetic models are based on chemical reaction kinetics and are suitable for practical application in the design/simulation of flotation cells and circuits as they incorporate the complex sub-process of the flotation micro-environment into simple rate constants. Empirical models are generally based on mathematical regression and are often useful for engineering purposes but have limited predictive capability. Phenomenological models are intermediate between kinetic/empirical and fundamental models as they are not derived from first principles but are consistent with fundamental theory. So for example, a kinetic model which links rate constants to properties of the flotation micro-environment, through correlations consistent with flotation theory, would be considered phenomenological.

2. Energy input in flotation

There is a considerable body of experimental and theoretical evidence to suggest that energy/power input (or agitation) plays an important role in flotation kinetics, particularly in the finer particle sizes where flotation efficiency is poor. Energy input is considered to influence all of the sub-processes of flotation, either directly or indirectly through bubble breakup and particle dispersion. Increased energy input is thought to increase particle-bubble collision frequencies, resulting in increased flotation rates. However, this increase also results in decreased stability of particle-bubble aggregates. The overall effect of energy input on flotation kinetics is therefore a balance of these two counteracting effects. In general, increasing energy input results in increased flotation rates to an optimum, after which flotation rates decrease. A large number of experimental studies have been conducted into the effect of energy input on flotation kinetics (Ahmed and Jameson, 1985; Deglon, 1998; Koh and Schwarz, 2003; Pyke et al., 2003; Newell and Grano, 2006; Changunda et al., 2008; Schubert, 2008; Massey et al., 2012; Tabosa, 2012; Safari et al., 2016; Tabosa, 2016, Safari et al., 2017; Testa et al., 2017; Hoseinian et al., 2017). These studies have found that the rate of flotation increases with energy input to the power of between 0.7 and 1.0. This is slightly higher than the theoretical models for particle-bubble collision in turbulent systems

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Table 1
Values for the constant N in the relationship $k \propto \varepsilon^{N}$.

Theoretical	Experimental
Nonaka et al. (1982) 0.75	Nonaka et al. (1982) 0.75
Julien Saint Amand 1999 0.44–0.5	Deglon 1998 0.9
Pyke 2004 0.44	Newell and Grano 2006 1.0
Schubert 2008 0.5	Changunda et al. 2008 1.0
Jameson 2010 0.75	Massey et al. 2012 0.7–0.9
	Safari et al. 2016 0.7–1.0

which suggest that the rate of flotation increases with energy input, or turbulent energy dissipation rate, to the power of between 0.44 and 0.75 (cf. Table 1).

Several studies have combined theoretical models for particle-bubble collision, attachment and detachment in simulations of agitated flotation cells (Saint Amand, 1999; Koh and Schwarz, 2003; Pyke et al., 2003; Sherrell and Yoon, 2005). These studies have generally confirmed that the effect of energy input on flotation kinetics is a balance between the two counteracting effects of increased particle-bubble collision frequency and decreased particle-bubble aggregate stability. However, there have been few kinetic models describing the effect of energy on flotation kinetics. This may be due to most kinetic models being based on single (forward-only) rate constants which allows for the process of particle-bubble collision-attachment but does not include a kinetic expression for particle-bubble detachment. An attachment-detachment kinetic model is developed which allows for the two separate kinetic processes of particle-bubble collision-attachment and detachment i.e. forward and reverse rate constants. The aim of this paper is to use the attachment-detachment kinetic model and the experimental data of Safari et al. (2016) to model the effect of energy input on flotation kinetics. The paper develops expressions for the attachment and detachment rate constants as a function of properties of the flotation micro-environment i.e. a phenomenological model for describing the effect of energy on flotation.

3. Model development

3.1. Attachment-detachment kinetic model

The differential equations defining the attachment-detachment kinetic model for a batch flotation cell are given in Eqs. (1) and (2). The model allows for the effects of both the pulp phase (Eq. (1)) and the gas phase (Eq. (2)) on flotation kinetics. The process of particle-bubble collision-attachment is assumed to be first-order with respect to the concentration of particles in the pulp phase (C) and controlled by an attachment rate constant (k_a). This is directly analogous to the definition of the flotation rate constant and the two are equivalent in the absence of significant detachment effects. The process of particle-bubble detachment is assumed to be first-order with respect to the concentration of particles on bubble surfaces (C_s) and controlled by a detachment rate constant (k_d). The argument for the use of first-order kinetics is equivalent to that for the flotation rate constant i.e. elementary reaction kinetics in the absence of complex interactions. The specific bubble surface area (S) is used to convert the term to a volumetric basis as a surface concentration (C_s) is employed in the expression. Eqs. (1) and (2) are ordinary linear differential equations and may be solved simultaneously to determine recovery as a function of the attachment and detachment rate constants, the flotation time and the gas residence time in the flotation cell (Eq. (3)). This is different from the standard-flotation model ($R = 1 - e^{-kt}$) in that it include a detachment term ($k_d \times \tau_g$). The gas residence time (τ_g) is the residence time of bubble surface area in the flotation cell but can be approximated by the gas residence time calculated on a volumetric basis using the gas flow rate and the gas hold-up. The standard flotation rate constant (k) can be back-calculated by applying the first-order expression ($1 - e^{-kt}$) to the recovery-time curve calculated using the attachment and detachment rate constants. Alternatively, the relationship between the flotation rate constant and the attachment and detachment rate constants can be estimated by $k = k_a/(1 + k_d\tau_g)$ (Deglon, 1998).

$$\frac{d(CV)}{dt} = -k_a CV + k_d C_s SV \tag{1}$$

$$\frac{d(C_s SV)}{dt} = k_a CV - k_d C_s SV - S_b C_s A \tag{2}$$

$$R(t) = f(k_a, k_d, t, \tau_g) \tag{3}$$

3.2. Experimental data

The attachment-detachment kinetic model was applied to the experimental data of Safari et al. (2016) to produce a data set of several thousand size-by-size rate constants derived from 460 flotation tests. Safari et al. investigated the effect of energy/power input on the flotation of three sulphide minerals (galena, pyrite & pentlandite) and three oxide minerals (apatite, hematite & quartz) in an oscillating grid flotation cell (OGC). Oscillating grids generate near ideal hydrodynamic environments, characterised by turbulence which is relatively homogeneous and isotropic i.e. ideal devices for investigating the effect of energy/power input. The conditions for the flotation experiments and a summary of the tests performed are given in Tables 2 and 3 respectively.

3.3. Attachment-detachment rate constants

General empirical correlations for the attachment and detachment rate constants were developed based on clear trends observed in the experimental data (cf. Eqs. (4) and (5)). These correlations describe the relationship between the attachment and detachment rate constants and the particle size, particle density, bubble size, contact angle and energy input. The correlations were applied to the entire flotation data set of several thousand size-by-size rate constants to determine best-fit regression values for individual empirical coefficients (c_1 & c_2) for each mineral type and common empirical exponents (n_1 to n_5) for all minerals. The coefficients (c_1 & c_2) varied quite significantly between the mineral types. For example, the coefficient c_1 for the attachment rate constant for the sulphide minerals was found to be 33.7, 7.0 and 2.40 ($\times 10^{-5}$) for galena, pyrite and pentlandite respectively. Similarly, the coefficient c_1 for the detachment rate constant was found to be 1.0, 1.5 and 1.8 ($\times 10^{-6}$) for these same minerals. These coefficients are

Table 2
Experimental conditions for flotation tests.

Condition/parameter	Value (sulphide minerals)	Value (oxide minerals)[a]
Solids	Galena, Pyrite, Pentlandite	Apatite, Hematite, Quartz
Solids concentration (mass%)	0.5	0.5
Gas	Nitrogen	Nitrogen
Superficial gas velocity (cm/s)	0.0065	0.0065
Bubble size (mm)	0.13, 0.58, 0.82	0.13, 0.24, 0.58, 0.82
Particle size (μm)	−150	−650, −75, −75
Energy input (W/kg or kW/m^3)	0.5, 1, 2, 3	0.1, 0.5, 1, 2, 3, 4, 5
Sampling time (min)	1, 2, 3, 4, 6, 9	1, 2, 3, 4, 6, 9
Frother	MIBC	MIBC
Frother concentration (ppm)	100	100
Collector	SEX, PAX, SIBX	OA, DAC, EDA
Collector dosage	Low, Moderate, High	Low, Moderate, High
Surface coverage	25%, 50%, 100%	25%, 50%, 100%
Contact angle (°)	40–50, 60–70, 80–90	40–50, 60–70, 80–90

[a] Note: Oxide minerals were floated at selected conditions from those given in the table.