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Distributed flotation kinetics models – A new implementation approach for coal flotation

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ABSTRACT

Composition-dependent flotation kinetic models with distributed flotation rate constants for predicting the flotation response of the various components of coal have been available for quite some time. However, the full potential of these models have not been realised because the floatability distribution of particles, a key requirement for the utilisation of the models, has not been readily accessible experimentally to allow the validation of these models.

A new approach has been developed that allows the coal flotation feed to be fractionated into particles classes of size and composition using a microscopic characterisation tool called Coal Grain Analysis. Previous work had determined the contact angles of discrete coal maceral groups and associated minerals. Combining this information with the particle composition data from the Coal Grain Analysis methodology provides a pathway for estimating the contact angles of heterogeneous coal particles via Cassie's Equation. The approach provides a unique opportunity to estimate the flotation rate constants for the different particle classes.

1. Introduction

Flotation kinetics models that draw direct analogy with chemical reaction kinetics, particularly the first order models, are the most widely used in the literature. The models are formulated in terms of the rate of flotation and can be quantified in terms of the physical, chemical and hydrodynamic parameters of the flotation system.

For instance, composition-dependent flotation models that are capable of predicting the flotation response of the various components of mineral ores and coal have been available for a long time. A simple example of these models is the first order kinetic flotation model given in Eqs. (1a) and (1b). In this model the total recovery $R(t)$ at flotation time t for a system in plug flow and for a system exhibiting perfect mixing respectively are given by (Garcia Zúñiga, 1935; Kelsall, 1961):

$$R(t) = R_\infty[1 - \exp(-kt)] \tag{1a}$$

$$R(t) = R_\infty\left[1 - \frac{1}{(1+kt)}\right] = R_\infty\left[\frac{kt}{1+kt}\right] \tag{1b}$$

k is the flotation rate constant and R_∞ is the ultimate recovery.

It is recognised that coal particles in flotation slurry possess a range of rate constants dependent on floatability (Imaizumi and Inoue, 1965). There is a distribution of rate constants due to the different particle size and composition classes present in the feed coal. This may be taken into account in the flotation models as:

$$R(t) = \sum_{i=1}^{n}\sum_{j=1}^{l} m_{ij} \cdot R_{\infty ij}[1 - \exp(-k_{ij}t)] \tag{2a}$$

or

$$R(t) = \sum_{i=1}^{n}\sum_{j=1}^{l} m_{ij} \cdot R_{\infty ij}\left[\frac{(k_{ij}t)}{1+k_{ij}t}\right] \tag{2b}$$

where m_{ij} is the mass fraction of particles of size class i and component j in the slurry and the sum of the mass fractions is equal to 1, k_{ij} represent the flotation rate constant of particles of size class i and component j, n is the number of size classes and l is the number of components.

The full potential of these models have not been realised for coal flotation because the floatability distributions of the particle classes, a key requirement for the utilisation of these models have not been readily accessible experimentally for the models to be properly validated. Current implementation approaches for coal utilise only a two-component system with fast and slow flotation

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rate constants k_f and k_s following Kelsall (1961) or as in the modification to include a non-floating component (Jowett, 1974). At the heart of the selective flotation process is the floatability distribution of the particles in the flotation environment; therefore a quantitative estimation of floatability distribution of coal is absolutely critical in the understanding and modelling of the behaviour of coal flotation systems. There has not been clear-cut and direct way of estimating the floatability of coal particles until now.

In minerals flotation, the liberation data provided by QEMSCAN and Mineral Liberation Analyser (MLA) has allowed size by liberation studies to be performed, such as the work of Sutherland (1989). Recent work in minerals flotation area includes those of Runge et al. (2004) and Welsby et al. (2010).

2. Background

2.1. Particle size and maceral composition-based Approach

A new approach has been developed that allows the coal flotation feed to be fractionated into particle classes of size and maceral composition using a semi-automated microscopic characterisation tool called Coal Grain Analysis. Microscopic analyses are conducted on polished grain-mounts of the samples using an oil immersion lens fitted to a reflected-light microscope. Microscope images were captured using the MACE300™ system for coal petrography. The images are then processed to obtain compositional information on each grain in the images. The abundances of vitrinite, inertinite, liptinite and minerals and their respective areas are determined. The full details of this characterisation tool and the information it provided can be found in Jenkins and Kwan (2003) and O'Brien et al. (2007).

The microscopic characterisation of the individual grains present in coal samples provides a unique opportunity to estimate the flotation rate constants for the different grain classes. This provides a new tool for more detailed flotation performance analysis and modelling. The coal flotation feed is divided into particles classes of size and maceral composition, each class with a distinct degree of floatability and therefore a distinct flotation rate constant. The summation of the recovery of the particles classes provides an estimate of the overall recovery. This approach provides a framework for an innovative and robust pathway for flotation process analysis and prediction of coal flotation outcomes.

The grains within each size fraction are classified into eight composition classes consisting of liberated (single component) and non-liberated (composite) grains. Additional composition classes can be accommodated if warranted. Single component grains comprise of >95% of a single phase and other grains are classified as composites. Microlithotype nomenclature is used for the single component grains with grains comprising of >95% vitrinite, inertinite, liptinite and minerals classified respectively as vitrite, inertite, liptite and minerite. The composite grains were subdivided based on their maceral/mineral associations as being either vitrinite-rich (VitRich), inertinite-rich (InertRich), liptinite-rich (LipRich) or mineral-rich composites (MinRich) depending on the dominant maceral type by volume in that class.

2.2. Hydrophobicity of heterogeneous coal particles

Estimation of the hydrophobicity/floatability of heterogeneous particles is critical in the understanding and prediction of the behaviour of particles in flotation systems. Previous work (Ofori et al., 2010; Arnold and Aplan, 1989) had determined the contact angles of discrete coal maceral groups of vitrinite, liptinite and inertinite and associated minerals. Combining this information with the particle composition data from the Coal Grain Analysis methodology provides a pathway for estimating the contact angle of heterogeneous coal particles via Cassie's Equation. Using the contact angle data of the flotation feed components as input data in new or existing flotation kinetic models provides a unique opportunity to estimate the flotation rate constants for the different particle classes.

The Coal Grain Analysis technique for microscopic characterisation of coal samples has made composition and area information of particle classes accessible (O'Brien et al., 2007; Ofori et al., 2004, 2006). For coal of composite grain classes made up of n maceral components such as vitrinite, inertinite and liptinite and also minerals, a contact angle θ_c can be estimated from the composition and fractional areas using Cassie's Equation (Cassie, 1948) which generalises to (Hey and Kingston, 2007):

$$\cos\,\theta_c = \sum_i^n x_i \cos\,\theta_i \tag{3}$$

where θ_i is contact angle of discrete maceral component i, x_i is the fractional area of component i at the surface. The contact angles for the different size and composition classes may be used as input in distributed flotation kinetic models.

2.3. Distributed flotation kinetics models

A number of studies have examined experimental and theoretical modelling approaches that aim to predict the flotation rate constants for minerals from first principles. One of the first of these studies was that of Sutherland (1948). Other investigators in this area include Jameson et al. (1977), Yoon and Luttrell (1989), Yoon (2000); Dobby and Finch (1987); Dai et al. (1999); Bloom and Heindel (2003); Nguyen and Schulze (2004); Ralston et al. (1999) and Runge et al. (2004).

In most of these studies, the models developed included flotation rate constants described by a relationship of the following form:

$$k_i = f(H, O, P_i) \tag{4}$$

where k_i is the flotation rate constant of particle class i, H is an expression for cell hydrodynamics, O represents operating conditions and P_i is the probability of capture of particle class i, which depends on the particle floatability.

The flotation rate constant described by the above relationship may be distributed in nature due to the floatability distribution of the particles. When applied to coal flotation, the Coal Grain Analysis tool may be used to classify the flotation feed into particle classes of size and maceral composition, each class with a distinct degree of floatability and hence a distinct flotation rate constant.

The particle capture process represented by probability P in Eq. (4) may be viewed as consisting of a sequence of sub-process events, each with an associated probability of success. If these probabilities are assumed independent of each other, the overall probability of particle capture is the product of these probabilities, (Schuhmann, 1942; Tomlinson and Fleming, 1965; Nguyen et al., 1997). Then

$$P = P_c \cdot P_a \cdot (1 - P_d) \tag{5}$$

where P_c is the probability of particle–bubble collision, P_a is the probability of particle–bubble attachment and $(1{-}P_d)$ or P_s is the probability that the particle will not detach from bubble.

Following the approach taken by Abrahamson (1978); Schubert and Bischofberger (1978); Schubert (1999); Yoon (2000) and Pyke et al. (2003), Eq. (4) may be written as:

$$k = \left[5n_B \cdot \left(\frac{d_{Bp}}{2}\right)^2 \frac{0.33\varepsilon^{4/9}}{\nu^{1/3}} \left(d_p^{14/9}\left[\frac{|\rho_p - \rho_f|}{\rho_f}\right]^{4/3} + d_B^{14/9}\right)^{\frac{1}{2}}\right] \cdot P_c \cdot P_a \cdot P_s \tag{6}$$