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CFD modelling of bubble–particle attachments in flotation cells

P.T.L. Koh *, M.P. Schwarz

CSIRO Division of Minerals, Bayview Avenue, Box 312, Clayton South, Victoria 3169, Australia

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Abstract

In recent years, computational fluid dynamic (CFD) modelling of mechanically stirred flotation cells has been used to study the complexity of the flow within the cells. In CFD modelling, the flotation cell is discretized into individual finite volumes where local values of flow properties are calculated. The flotation effect is studied as three sub-processes including collision, attachment and detachment. In the present work, these sub-processes are modelled in a laboratory flotation cell. The flotation kinetics involving a population balance for particles in a semi-batch process has been developed.

From turbulent collision models, the local rates of bubble–particle encounters have been estimated from the local turbulent velocities. The probabilities of collision, adhesion and stabilization have been calculated at each location in the flotation cell. The net rate of attachment, after accounting for detachments, has been used in the kinetic model involving transient CFD simulations with removal of bubble–particle aggregates to the froth layer.

Comparison of the predicted fraction of particles remaining in the cell and the fraction of free particles to the total number of particles remaining in the cell indicates that the particle recovery rate to the pulp–froth interface is much slower than the net attachment rates. For the case studied, the results indicate that the bubbles are loaded with particles quite quickly, and that the bubble surface area flux is the limiting factor in the recovery rate at the froth interface. This explains why the relationship between flotation rate and bubble surface area flux is generally used as a criterion for designing flotation cells. The predicted flotation rate constants also indicate that fine and large particles do not float as well as intermediate sized particles of 120–240 μm range. This is consistent with the flotation recovery generally observed in flotation practice. The magnitude of the flotation rate constants obtained by CFD modelling indicates that transport rates of the bubble–particle aggregates to the froth layer contribute quite significantly to the overall flotation rate and this is likely to be the case especially in plant-scale equipment.

Keywords: Flotation bubbles; Flotation kinetics; Flotation machines; Modelling

1. Introduction

Researchers have recently started to use computational fluid dynamics (CFD) for modelling mechanically stirred flotation cells to study the complexity of three-phase (air–water–solids) flows within the cells (Koh and Schwarz, 2003). Flotation cells are conventionally designed using empirically derived relations. In CFD modelling, the flotation cell is discretized into individual finite volumes where local values of flow properties are calculated. The detailed understanding of flow gained using this approach allows modification to existing equipment and operation to improve flotation performance.

The flotation effect is modelled as three sub-processes involving collision, attachment and detachment. A turbulent collision model is used to estimate the rate of bubble–particle encounters, employing the local turbulent velocity, and the size and number concentrations of bubbles and particles in different parts of the cell. The probabilities of collision, adhesion and stabilization are also calculated such that attachment rates can now be estimated. The detachment rates are also estimated from the

* Corresponding author.
E-mail address: Peter.Koh@csiro.au (P.T.L. Koh).

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fluid turbulence. The net rate of attachment, after accounting for detachments, is used in the combined CFD kinetic model involving transient population-balance simulations with removal of bubble–particle aggregates to the froth layer.

In this paper, the local turbulent energy dissipation rates used in the kinetic model are obtained by CFD modelling of the cell. This is a significant improvement over other models where assumptions based on an average dissipation rate or an assumed Gaussian distribution for turbulent velocities for the whole cell (e.g. Bloom and Heindel, 2003) have been used. CFD modelling provides a realistic approach to flotation models without the additional assumptions on turbulent energy dissipation rates.

Flotation in a cylindrical tank fitted with a Rushton turbine impeller is studied in this paper since commercial flotation equipment are mostly of this type fitted with rotor–stator system. For comparison, a laboratory flotation cell designed by CSIRO Minerals is also modelled.

2. Flotation kinetics

Flotation is generally modelled as a first-order rate process with respect to the number of particles and number of bubbles in the attachment step, and a detachment process with respect to the number of bubble–particle aggregates. The kinetic equation for the bubble–particle encounters is described by the rate of removal of the number of particles in a given volume as follows:

$$\frac{dN_{p1}}{dt} = -k_1 N_{p1} N_b + k_2 N_a \tag{1}$$

where N_{p1} is the number concentration (m^{-3}) of free particles, N_b is the number concentration of bubbles available for attachment, N_a is the number concentration of bubble–particle aggregates, k_1 is the particle–bubble attachment rate constant, and k_2 is the particle–bubble detachment rate constant. In a given volume within the flotation cell, the total number of particles consists of free particles (N_{p1}) and particles that are attached to bubbles (N_{p2}), both as functions of time

$$N_{pT} = N_{p1} + N_{p2} \tag{2}$$

with N_{pTo} as the initial particle concentration. In general, bubbles will have any number of particles attached as they move up toward the froth layer, with the number of particles per bubble varying with time and position, as well as from bubble to bubble. To simplify the situation, it is assumed in this paper that certain bubbles are fully loaded with particles while the remaining bubbles are clean. The number of bubble–particle aggregates (N_a) is then related to the total number of bubbles (N_{bT}) by an average loading parameter (β) as follows:

$$N_a = \beta N_{bT} \tag{3}$$

The average loading parameter (β) in a given volume varies with time and position in the cell. The number of bubbles that are available for attachment (N_b) is also related to the total number of bubbles as follows:

$$N_b = (1-\beta) N_{bT} \tag{4}$$

So, the attachment–detachment kinetics in Eq. (1) can be re-written as follows:

$$\frac{dN_{p1}}{dt} = -k_1 N_{p1} N_{bT}(1-\beta) + k_2 N_{bT}\beta \tag{5}$$

An interpretation of the new equation is that the kinetics is now based on the free surface area available for particle attachment with a bubble loading parameter β such that $\beta = 0$ for clean bubbles and $\beta = 1$ for fully loaded bubbles. The number of particles that can be attached to a single bubble is given by S which is the ratio of the total surface area of the bubble to the particle projected area as follows:

$$S = 4\left(\frac{d_b}{d_p}\right)^2 \tag{6}$$

where d_p is the particle diameter and d_b is the bubble diameter. Realistically, it is not possible for the particles to cover the whole bubble surface due to packing, shape and other factors. As a first approximation, it is assumed that the attached particles occupy about half of the total bubble surfaces when the bubbles are fully loaded. The maximum number of particles per bubble ratio (S_{max}) is then described by

$$S_{max} = 0.5S = 2\left(\frac{d_b}{d_p}\right)^2 = \frac{N_{p2}}{\beta N_{bT}} \tag{7}$$

By rearranging the above equation, the bubble loading parameter β can be obtained from

$$\beta = \frac{N_{p2}}{S_{max} N_{bT}} \tag{8}$$

The present method is a significant improvement over previous models in modelling the number of particles that can be attached to a bubble. The first model proposed by Bloom and Heindel (1997) had assumed that only bubbles which do not already have a particle attached to them are capable of picking up a particle, and that the average number of particles on a bubble was equal to 1.0. This assumption was replaced in their latest model (Bloom and Heindel, 2003) by an average loading based on total numbers of particles and bubbles in the flotation cell.

In the kinetic equation, the particle–bubble attachment rate constant k_1 (m^3/s) is defined by

$$k_1 = Z_1 P_c P_a P_s \tag{9}$$

and the particle–bubble detachment rate constant k_2 (1/s) is defined by

$$k_2 = Z_2 P_d = Z_2(1 - P_s) \tag{10}$$

where P_c, P_a and P_s are the probabilities of particle–bubble collision, adhesion and stabilisation against external forces. P_d is the probability a bubble–particle aggregate will become unstable and is assumed to be equal to $(1 - P_s)$. P_s