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A computational fluid dynamics model for the flotation rate constant, Part I: Model development

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ABSTRACT

A Computational Fluid Dynamics (CFD) model for the prediction of the flotation rate constant in a standard Rushton turbine flotation tank was developed. The premise for the model development was the assumption that separation by flotation is a first order rate kinetic process. An Eulerian–Eulerian framework in conjunction with the dispersed k–ε turbulence model was supplemented with user defined functions to implement the local values of the turbulent flow into a kinetic model. Simulations were performed for quartz at different operational conditions. The numerical predictions were validated against experimental data and analytical computations using the fundamental flotation model of Pyke et al. (2003). The results showed that the CFD-based model not only captured the trend of experiments for a range of particle sizes but also that the CFD yielded improvements in the predictions of flotation rate constant compared with the theoretical calculations. It was found that the CFD model is able to predict the flotation rate constants of the quartz particles floating under different ranges of hydrophobicity, agitation speed and gas flow rates with lower root mean square deviation compared with the theoretical computations.

1. Introduction

The flotation process has been broadly applied in mineral processing plants to separate valuable minerals from the gangue based on the differences in the surface hydrophobicity of the solid particles. Appropriate chemical and hydrodynamic conditions inside the flotation tank will lead to the collection of the hydrophobic minerals with the aid of air bubbles. This process involves three sub-processes comprising bubble–particle collision, bubble–particle attachment and the formation of the stable bubble–particle aggregates. The detachment of the solid particles from the air bubbles might also occur due to the inadequate chemical or hydrodynamic environments within the tank. Once the selective chemical properties of the pulp have been constituted, the hydrodynamic parameters control the removal rate of the solid particles from the slurry. Of the various factors, the hydrodynamic properties of the vessel depends significantly on the impeller rotational speed, air flow rate, gas holdup and the bubble surface area flux (Arbiter and Harris, 1969; Gorain et al., 1995a,b, 1996; Gorain et al., 1997). Due to the influence of hydrodynamically important factors on the micro-scale phenomena inside a flotation tank, King (2001) emphasized the difficulties encountered in the flotation modelling procedure. He, however, suggested that a successful predictive model should follow a first order rate kinetic format for the transfer rate of particles that is the product of the number of bubble–particle collisions, the number of bubbles per unit volume and the efficiency of the solid particle collection. The conservative form of the flotation kinetic model can be written as (Duan et al., 2003; Jameson et al., 1977):

$$\frac{dN_p}{dt} = kN_p = -Z_{pb}E_{coll} \quad (1)$$

where N_p is the number of solid particles, k is the flotation rate constant, Z_{pb} is the number of bubble–particle collisions and E_{coll} is the collection efficiency. The impact of the flotation sub-processes (i.e., collision, attachment, and detachment) has been incorporated in Eq. (1) by segregating the collection efficiency into three probability functions evaluating the efficiencies of the sub-processes (Derjaguin and Dukhin, 1993; Dukhin et al., 1995):

$$E_{coll} = E_c \times E_a \times E_s \quad (2)$$

In this equation the efficiencies of the bubble–particle collision, attachment and stability are indicated by E_c, E_a, and E_s, respectively. A significant amount of research has been conducted

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to formulate each of the probability functions in Eq. (2) with the flotation tank hydrodynamics and the operational conditions and is briefly reviewed in the following paragraphs.

Schubert and Bischofberger (1978), for instance, correlated the effects of impeller speed and air flow rate with the flotation recovery and grade using dimensionless numbers (i.e., power and flow numbers). Bloom and Heindel also derived analytical expressions for the collision and attachment probabilities in 1999 (Bloom and Heindel, 1999; Heindel and Bloom, 1999). Their proposed attachment equation comprised various flotation characteristics such as fluid properties, bubble and particles diameters and velocities, and the ratio of the initial-to-critical liquid film thickness during the sliding motion of the particles over the bubbles. The collision equation, however, involved three non-dimensional groups: the particle settling velocity magnitude, the bubble Reynolds number, and the particle/bubble radius ratio. The capability of the equations was confirmed with validations against available experimental data. Another notable works is the study of Dai et al. (1999) who modified the Generalized Sutherland Equation (GSE) (Sutherland, 1948) to determine the attachment efficiency of quartz particles with nitrogen bubbles. The authors also reviewed and elaborated the bubble–particle collision models with respect to the hydrodynamic characteristics and the fluid flow regimes in which the models were developed (Dai et al., 2000). Furthermore, Bloom and Heindel (2002) presented two new analytical equations for the collision and detachment frequencies. They combined their equations to predict the flotation efficiency in a semi-batch process (Bloom and Heindel, 2003). Their strategy accounted for collision, attachment and stabilization in the flotation process by solving a partial differential equation for the concentration of free particles inside the flotation tank. Experimental data for deinking flotation were used to validate the new methodology. Similarly, Pyke et al. (2003) incorporated the efficiencies of the flotation sub-processes to formulate a fundamental model for the calculation of the flotation rate constant. The generalized Sutherland equation was applied to compute the collision efficiency, while the attachment rate was calculated based on the Dobby and Finch model (Dobby and Finch, 1987). The bubble–particle stability efficiency was also determined in Pyke's model based on the adhesive and detaching forces with the aid of the dimensionless Bond number (Schulze, 1977). Flotation experiments with quartz particles were carried out to examine the model's predictive potential. The comparison of the computed flotation rate constants with the experimental measurements ensured the viability of the new model. In the same year, Nguyen derived another expression for the attachment tenacity based on the force balance (Nguyen, 2003). He emphasized on the role of turbulence on the detachment process and suggested that better prediction of the turbulent dissipation rate will improve his proposed method.

Although the theoretical equations reviewed for the flotation efficiency have integrated the hydrodynamic parameters, they have been treated as a constant averaged value for the entire tank. For example the energy dissipation rate was obtained according to the power input. However, Schubert (2008) pointed out that the hydrodynamic values vary significantly in the spatial and temporal scales. He mentioned that the turbulent properties around the rotational system can be much higher than the bulk region. He exemplified the ratio of the average dissipation rate to the maximum dissipation rate that can reach up to 200. Thus, using an average value for the entire domain may cause serious uncertainties for the predictions of the flotation performance. For this reason, as well as the weakness of the analytical framework for incorporating the fluctuating behaviour of the hydrodynamic parameters, the application of numerical methods, such as Computational Fluid Dynamics or CFD, for modelling of the flotation process has become a fruitful and challenging subject of research. Although the multiphase simulation of the gas and liquid phases in stirred tanks has been extensively studied, for instance (Bakker and Akker, 1994; Joshi et al., 2011; Lane et al., 2002; Ranade and Deshpande, 1999), the application of CFD for the macro scale flotation modelling has been mostly limited to the studies of Koh and Schwarz. As the first attempt in 2000 (Koh et al., 2000), they compared two different flotation cells, a CSIRO flotation cell and a standard Rushton turbine tank in terms of the number of bubble-particle collision per time per unit volume. An Eulerian–Eulerian multiphase approach in conjunction with the standard k–ε turbulence model was used to predict the flow variables. In the post-processing step the computed flow properties were applied to calculate the number of bubble–particle collisions. Three years later, they combined the bubble–particle collision rate and the bubble–particle attachment rate in a CFD model to simulate a Denver-type flotation cell (Koh and Schwarz, 2003). The number of bubble–particle collision was computed using Saffman and Turner equation (Saffman and Turner, 1956), while the proposed model of Yoon and Luttrell (1989) was applied to account for those particles following the liquid streamlines. Similar to their previous work, an Eulerian–Eulerian approach was used for the multiphase modelling along with the Multiple Reference Frames (MRF) technique for the rotation of impeller. They completed the modelling of the flotation sub-processes in 2006 by including the detachment rate and the attachment probability into a CFD model (Koh and Schwarz, 2006). A first order kinetic model was equipped with all the equations of the sub-processes using source and sink terms. The governing equations for the gas–liquid as well as the flotation kinetic equation were solved using CFX4.4 for two geometries including a Rushton turbine tank and a CSIRO Denver type flotation cell. They determined the flotation rate constant according to the number of particles remained in the cell. In a follow up study the same methodology was applied for a self-aerated flotation cell (Koh and Schwarz, 2007). The only difference was that an extra source term was added in the dispersed phase equation to represent the influence of the gravitational force. They found that the inclusion of this force increased the detachment frequency. In their latest works, the numerical predictions of the flotation rate constant for a modified Denver flotation cell were also validated by batch flotation tests (Koh and Smith, 2010; Koh and Smith, 2011). The effect of impeller speed on the flotation performance was investigated in these two studies with the developed CFD method of Koh and Schwarz. Good agreement, both qualitatively and quantitatively, was reported between the predicted flotation rate constants and the measurements. Apart from the Eulerian–Eulerian method applied by Koh and Schwarz, a Lagrangian–Eulerian approach was also used in the micro scale modelling of the flotation. In this method efforts were made to utilize a higher order coupling manner between the different phases (e.g. Wierink and Heiskanen, 2008; Wierink et al., 2009; Wierink and Heiskanen, 2010). The solid particles were modelled in a Lagrangian framework using DEM, while the liquid phase was treated in an Eulerian way within a CFD solver. The capability of CFD–DEM model was tested for a case where a cloud of particles falls on an individual air bubble (Wierink, 2012). The results of this study showed that Lagrangian–Eulerian methodology enables researcher to apply a full momentum coupling between the particulate phases leading to promising results. Nevertheless, the required computational time bounds the day-to-day application of this approach which can be remedied in near future with availability of higher computational powers.

The incorporation of numerical methods in fundamental models of flotation has been limited. This is probably due to the significant difficulty of integrating complex models for flotation sub-processes with the already challenging problem of numerical modelling of a fully turbulent flow inside a mechanically agitated

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