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Effect of negative inertial forces on bubble-particle collision via implementation of Schulze collision efficiency in general flotation rate constant equation

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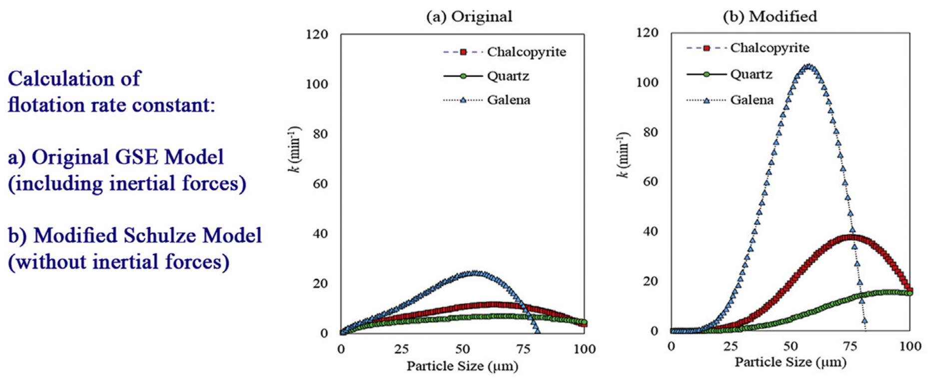
HIGHLIGHTS

- The effect of negative inertial force on flotation rate constant was investigated.
- The GSE and Schulze collision models were compared through flotation rate constant.
- Effect of mineral density on flotation rate constant models was investigated.
- Neglecting negative inertial forces conduces inaccuracy in flotation rate constant.
- GSE and Schulze collision models exhibited agreement only at fine particle sizes.

GRAPHICAL ABSTRACT



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ABSTRACT

In this study, Schulze collision inertial model was employed to investigate the effect of neglecting the negative inertial forces in collision efficiency and flotation rate constant predictions. The model evaluation was carried out with the Generalized Sutherland Equation (GSE) model in which the estimation of both positive and negative inertial forces have been well accounted. The general flotation kinetic model has been used in this study to demonstrate changes when the negative particle inertia is omitted. Theoretical comparisons were made on two minerals, i.e. quartz and chalcopyrite. The effect of particle density on the modified kinetic model was very significant when a dense mineral like galena was used. This reveals that the general flotation rate model is very sensitive to the substitution of Schulze model. Results obtained were far from satisfactory and show that the Schulze model cannot cope with the change of density very well. It was found that when Schulze collision model was implemented in flotation rate constant calculation, there is a wide range of particle size which is not strongly influenced by parameters such as bubble size and velocity, and particle density and results are very close to each other. This is not in good agreement with the experimental results or GSE model data.

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1. Introduction

Flotation separation is a process used in number of industries to separate desired particles from the rest of materials. In mining and mineral processing industry, it is used to separate and concentrate valuables from gangue minerals. Bubble-particle interaction is of a great importance in these processes. It is controlled by a number of forces and factors such as the hydrodynamic resistance, inertial forces, gravitational forces, bubble-particle interactions, colloidal forces, and particles surface state [1–3]. It is considered that the collision, attachment, and detachment sub-processes are independent and represent the bubble-particle important steps in flotation [4–6]. Bubble-particle interactions are widely shown to be the most important sub-process in froth flotation. These interactions are quantified based on statistical approaches on successful transfer of particles through bubbles towards the froth phase and concentrates. Capture efficiency (E_{cap}) or collection efficiency is defined as the ratio of the number of bubble-captured particles over the number of particles initially located in the volume that the bubble swept [7]. It is composed of the probability of three sub-steps (Eq. (1)) [8–12].

$$E_{cap} = E_c.E_a.E_s \tag{1}$$

Where E_c, E_a, and E_s are collision, attachment, and stability (detachment) efficiencies, respectively. A deep understanding of these sub-processes is fundamentally necessary in predicting rate constant for flotation kinetics [13–16,9,17–19].

Collision sub-process is the first step of interaction of a particle and a rising bubble which is mainly controlled by the fluid hydrodynamic properties. It is mostly governed by the liquid flow and the relative motion of bubbles and particles in a flotation cell. Numerous models have been proposed for the evaluation of the collision efficiency. In addition, a number of excellent reviews on the modeling of the bubble–particle collision sub-process have been established [4,6,20,5]. All of the collision models are based on a hydrodynamic analysis of the particle-bubble system, with respect to the fluid flow regimes at the bubble surface and media (Stokes, potential, intermediate flows and relative Reynolds number), the degree of mobility of the bubble surface, particle size and its density, turbulence of cell, the effective forces (interceptional, gravitational, and inertial effects), the influence of positive and negative inertial forces, bubble size and its velocity [5]. At the moment of impact, particle deforms the bubble surface, creates a water layer between particle and bubble, and bubble surface forces cause the particle recoil from the bubble surface. Schuhmann [21] was the first to suggest bubble-particle collision efficiency as a fundamental parameter in the calculation of the flotation rate constant. The first model that included positive inertial effects was reported by Langmuir and Blodgett [5]. On the assumption of Stokes flow velocity for particles, Langmuir and Blodgett [22] derived the first expression for the collision efficiency due to inertial deposition between stationary droplet and large droplets on movement [5]. In an attempt to approach a collision model that includes particle inertia, Flint and Howarth [23] derived expressions for collision efficiency by solving the equations of particle motion for both potential flow and Stokes flow. The model was experimentally investigated on the galena particles in interaction with air bubbles which gave good results under Stokes number well below unity. The Sutherland equation was extended by Dukhin (1983) [42] to account for the influence of both positive and negative inertial forces based on the inertial hydrodynamic interaction between solid particles and mobile bubbles. In this regard, the analytical equation so called Generalized Sutherland Equation (GSE) was suggested by Dai et al. [24]. As mentioned by Ralston et al. [25], deviation of the trajectory of a fine particle from the straight path towards the bubble surface at a distance of the order of the bubble size is caused by long-range hydrodynamic interaction (LRHI). However, in case of a coarse particle the inertial forces considerably exceed the LRHI, which, therefore, can be neglected. In the case of fine particles, however, the forces of inertia are small compared to the LRHI. Furthermore, the hydrodynamic interactions at distances comparable to the particle radius have to be taken into account. In fact, this permits the particle's trajectory to deviate from the liquid flow line and is called the short-range hydrodynamic interaction (SRHI). Li and Schwarz [26] reported that for quartz particles finer than 20 μm, bubble with mobile surface, and Reynolds number of 151, higher particle density yields lower collision efficiency. In contrary, for particles coarser than 20 μm, the higher the particle density, the higher the collision efficiency is. The phenomenon results from the effect of inertia on the particles very close to a bubble with mobile surface, which gives rise to a centrifugal force and opposes depositions. Yoon and Luttrell [6], experimentally and theoretically showed the similar trend for E_C as a function of bubble velocity for quartz particles, with different assumptions. They neglected inertial effect and also considered that bubble-particle collision to occur evenly above the equator line of the bubble surfaces. These assumptions deviate their results from the GSE model. A recent research using the computational simulation has been contributed to validation of Sutherland's theory and its generalized form (GSE) including effect of inertial forces [27]. The results of computational modeling considering gravitational force showed that the particle density significantly affects collision efficiency counterbalancing the negative effect of inertial forces during the collision of the particles with the air bubbles in GSE model [28].

Attachment and aggregate stability are strongly related to the physicochemical and surface properties of both particle and bubble. Hydrodynamics, interfacial interactions including capillary and hydrophobic forces, particles and bubbles behavior and solution chemistry are all interwoven in colloidal systems such as bubble-particle interaction [29]. In order to explain the contributions of each collision, attachment, and stability efficiencies in particle-bubble attachment, as well as the collision frequency, an analytical model has been derived under turbulent flotation conditions referred as a general flotation kinetic model which provides the calculation of the flotation rate constant as a function of particle size with measurable particle, bubble, and hydrodynamic quantities [11,12].

The flotation rate is the rate of valuable recovery in the flotation product per unit time which is characterized by a rate constant and kinetics order [30]. Numerous researchers have studied the kinetics aspects of froth flotation paying special attention to particle size, bubbles, and their complex interactions in flotation cells [31–34]. The first attempts to model the kinetics of flotation were based on variations in the amount of froth overflow over time Arbiter and Harris, [35]). In another study, [36] investigated the role of gas dispersion properties on the flotation rate constant at both plant and pilot scales for mechanical flotation cells under different operating conditions. They found that there is a strong and linear relationship between bubble surface area flux and the flotation rate constant. In such cases, surface area flux is a property of the gas dispersed phase in a flotation cell which combines the effect of bubble size and superficial gas velocity into one parameter. It is widely accepted that particle–bubble encounter directly affects the flotation rate constant and in turn flotation recovery [12,37]. Duan et al. [12] used the GSE model for predicting particle-bubble collision under potential flow, on a mobile bubble surface. In the above study, the calculated flotation rate constants were found to highly depend on collision efficiency. The lower flotation rate constant values of fine and coarser particles have been attributed to the low collision and stability efficiencies, respectively. Hassanzadeh et al. [38] showed that the poor suspension state of the coarse particles in flotation cell reduces their effective cell residence time and in turn decreases