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Review

A review of the mechanisms and models of bubble-particle detachment in froth flotation

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A B S T R A C T

Only when the process of particle detachment is well understood and modelled can minerals recovery using the flotation process be modulated to achieve a high efficiency by suitably changing the operating parameters. This is vitally necessary for the recovery of coarse particles in an energy efficient way, as detachment is the key limiting factor in the successful recovery of large particles. However, until the detachment mechanism is more fully understood, an upper limit on the floatable particle diameter still remains unidentified. To assess the current state of knowledge available in this area, a comprehensive literature review on the mechanisms and models of the bubble-particle detachment process in froth flotation is presented. In general, the detachment process is considered to be a stochastic process, and is usually attributed to the dynamic interactions with the turbulent flow structures (eddies) in the flotation environment which cause particles to detach because of dissipating energy. In this paper, previous studies on bubble-particle detachment have been critically analyzed with respect to the formulation of the models in predicting the detachment probability of particles. The models are classified into three different categories: force balance analysis; energy balance analysis and empirical analysis of particle size compared to maximum floatable particle size. Attention is also paid to an understanding of the mechanisms of bubble-particle detachment in quiescent and turbulent liquid flow fields. The predictions of all these models have been compared with the published experimental data and it was found that models which take an accurate consideration of the influence of eddies on a particle's detachment give the closest predictions. The generally held concept of bubble-particle detachment inside an eddy was experimentally validated, where a particle was observed to rotate on the surface of a bubble, resulting in a centrifugal acceleration 20 times that of gravitational acceleration. The aim of this paper is to review the developments and limitations of the existing models. The experimental work is reviewed so as to reveal the mechanisms of bubble-particle detachment. Therefore, the future development of models is identified in order to successfully predict particle detachment.

Contents

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Nomenclature

A	magnitude of vibration (m)
A_s	empirical constant (–)
Bo	Bond number (–)
B_o^*	modified Bond number (–)
C	correction to the estimation of the particle detachment energy, Eq. (61) (–)
C_p	particle concentration in the pulp (kg/m^3)
E_1	energy barrier (J)
E_k'	detachment energy (J)
ΔE_{de}	particle energy of detachment (J)
F_a	centrifugal force (N)
F_{att}	attaching force (N)
F_c	capillary force (N)
F_b	buoyancy force (N)
F_{de}	detaching force (N)
F_g	gravity force (N)
F_p	pressure force (N)
H	distance between the bubble apex and the plane of the three phase contact circle (m)
P_a	attachment probability (–)
P_c	collision probability (–)
$P_{collection}$	collection probability (–)
P_d	detachment probability (–)
R_{imp}	radius of impeller (m)
R_p	particle radius (m)
S	strength of bubble-particle aggregate (N)
U_D	impeller tip velocity (m/s)
V_g	gas superficial velocity (m/s)
ΔV	turbulent relative velocity between the particle and the bubble (m/s)
W_a	work of adhesion (J)
b_m	eddy turbulent acceleration (m/s^2)
b_{max}	sum acceleration due to circulation and vibration (m/s^2)
c_1	constant in fluctuating velocity equation, Eq. (21) (–)
c_2	particle rotational radius correction factor (–)
d_{ag}	diameter of bubble-particle aggregate (m)
d	characteristic length scale of particle (m)
d_B	bubble diameter (m)
d_P	particle diameter (m)
d_{bmax}	maximum stable bubble diameter (m)
d_{pmax}	maximum floatable particle diameter (m)
d_{pmin}	minimum particle diameter below which detachment probability is zero (m)
g	gravity acceleration (m/s^2)
k	flotation rate constant (–)
l	particle rotating distance from the axis of an eddy (m)
m_p	particle mass (kg)
m_b	bubble mass (kg)
r	radius of rotation (m)
r_s	radius of particle movement on bubble surface due to bubble vibration (m)
p_1	pressure acting on the particle at the bottom (pa)
$\overline{u_l}$	fluctuating velocity corresponding to eddy of scale l (m/s)
u'	fluctuating velocity corresponding to eddy of κ-space (m/s)
u_{ps}	circular velocity of the attached particle on the vibrating bubble (m/s)

Greek letters

ω	rotational speed (rad/s)
σ	surface tension (N/m)
θ_A	advancing contact angle (°)
θ_R	receding contact angle (°)
α	central angle (°)
θ	contact angle (°)
ρ	particle density (kg/m^3)
ρ_l	liquid density (kg/m^3)
ρ_P	particle density (kg/m^3)
ε	energy dissipation rate (m^2/s^3)
κ	wavenumber of oscillating eddy (1/m)
α_R	maximum central angle at attaching process (°)
α_m	central angle at maximum capillary force (°)
ν	kinetic viscosity (m^2/s)
$\varnothing$	area of contact between particle and bubble (m^2)
$\Delta\rho$	density difference between particle and liquid (kg/m^3)

1. Introduction

Froth flotation is an important process in the mining industry, and is widely used in the recovery of valuable minerals from the ores. It is also applied in processes like the deinking of waste paper and in waste water treatment. The essence of flotation lies in using bubbles to capture particles based on their surface hydrophobicity difference. Hydrophobic particles are more likely to attach to the bubble interface due to a strong adhesion force compared to hydrosphilic particles. The kinetics of flotation is often described as a firstorder process, relating the rate of particle attachment to particle concentrations [2,8,58,60,61,106]. Following this definition, the rate of a particle capture process in a batch process can be described as:

$$\frac{dC_p}{dt} = -kC_p \tag{1}$$

where the rate constant, k, represents the rate of the removal of particles from the pulp, and C_p is the particle concentration in the pulp in units of mass/volume. It is noted that Eq. (1) only applies to the simulated removal of particles in a batch process. In a continuous flotation cell, the inlet and outlet concentrations do not change with time in a steady state, so that Eq. (1) does not apply to the cell as a whole. Batch flotation has been most extensively studied in the laboratory. The experimental data has been tested against a more general model:

$$\frac{dC_p}{dt} = -kC_p^n \tag{2}$$

where n is the order of the "reaction" between the particles and bubbles. Arbiter [7] considered the second-order fit experimental data. Morris [80] considered a first-order rate equation similar to Eq. (1). When integrated, it gave:

$$k = \frac{1}{t}\ln\frac{C_0 - x}{C_t - x} \tag{3}$$

where C_0 is the original concentration of the mineral, C_t is the concentration after time t, and x is the percentage of unfloatable mineral.

Bushell [21] used a modified first-order equation to fit his data, and gave:

$$\frac{dC_p}{dt} = -k(C_p - C_T) \tag{4}$$

Here, C_T is the concentration of unfloatable material. The fit of the function improved when C_T was taken as an empirical constant.