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Gas-liquid slip velocity determination in co-current column flotation

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ABSTRACT

The motion of air and water is characterised in a downflow co-current column reactor. The velocity of the bubble swarm relative to that of the bulk water is determined using a new approach for the computation of the slip velocity in a CFD simulation using a modified drift flux model and incorporating the data obtained from the CFD modeling. The validity of the numerical model is confirmed by comparing the simulation results with those of experimental. The average slip velocity is found to be approximately 3.3 cm/s in the down-comer co-current column, which is lower than those prevailing in counter-current columns. It is concluded that in a bubbly flow regime lower slip velocity improves the bubble particle collection efficiency.

1. Introduction

Flotation is a technology for creation of particle-laden bubbles in order to remove the contaminant concentrated froth. Column flotation is widely used in minerals and wastewater processing [26,33,13]. Air bubbles suspended in the liquid column attract particles of contaminant onto their surface and give rise to an effective method for the collection of the solid particulate. Many investigators identified new hydrodynamic aspects of two-phase columns including the interaction between the two phases [46,36,6,23,40]. The relative motion of bubbles relative to the surrounding liquid, i.e. the slip velocity, has been shown to be of prime importance in order to achieve an acceptable collection efficiency [13,17]. The improvement of the efficiency of particle recovery/removal by froth flotation requires the collision and attachment of particles on bubbles. This is partially dependent on the distribution of the population of bubbles and the degree of mixing by turbulent action in the column [18,5].

Most flotation columns operate counter-currently, i.e. the pulp entering the top and the gas injected at the base of the column through a sparger, forming a concentrated stream of gas bubbles [13,41,19,37,38]. The Jameson flotation bubble column [21] has both the gas and pulp entering at the top of the column [5,12,20,10]. Particles collide with the bubbles in a downward co-current column and bubble-particle aggregates are created. The particle-laden bubbles are then discharged into the separation tank where they float to the top of the tank for removal (Fig. 1). Low air to water ratio (i.e. ~0.2) is defined to be the ideal mode of operation, particularly in the co-current mode [18,45]. Increasing the air flow rate brings about excessive gas recirculation leading to unstable operation [12,29,30].

When a hydrophobic particle approaches a bubble it slides over the surface of the bubble, during which attachment may occur due to the attraction out of the water into the surface of the bubble by forming a three-phase contact with a finite contact angle. However, the velocity of particles relative to bubbles plays a key role in their attachment [15]. The determination of the appropriate slip velocity is therefore one of the key contributing factors for the accomplishment of a particle-bubble collision leading to attachment [27,23]. A further sub-process that should be avoided is the detachment of particles from bubbles, which in turn may be governed by the slip velocity. This paper investigates the velocity of the bubble swarm relative to that of water in a downward flowing column.

The term slip is widely used in two phase flow to represent the lag of velocity of one phase compared to the other. Zeghloul et al. [46], introduced a slip ratio that is the ratio of the mean gas velocity to that of the liquid phase. They used it as a measure to clarify the study of the air–water mixture flowing through an orifice in a vertical pipe. The most frequent method used for estimation of slip velocity is the drift flux model to present the average velocities associated with the gas and liquid in a column [42,11].

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Nomenclature

F	external body force
F_{lift}	lift force
F_{wl}	wall lubrication force
g	gravity acceleration
K	interphase exchange coefficient
m	mass flux
$\dot{m}$	mass transfer from phase 1 to phase 2
$\dot{m}'$	mass transfer from phase 2 to phase 1
n	model's constant
Q_G	volumetric flow rate of gas
Q_L	volumetric flow rate of liquid
r	local radius
R	outer radius of the column
U_s	slip velocity
U_G	gas superficial velocity
U_L	liquid superficial velocity
U_b	actual terminal velocity of single bubble
V	local velocity
v	phase velocity
$\vec{v}$	velocity of phase 1
$\vec{v}'$	velocity of phase 2

Greek letters

ε	gas hold up
φ	dimensionless radial position in the column (= r/R)
ρ_{rq}	volume averaged density of the q_{th}
α	phase volume fraction
ρ	phase density
$\bar{\bar{\tau}}$	stress-strain tensor of q_{th} phase

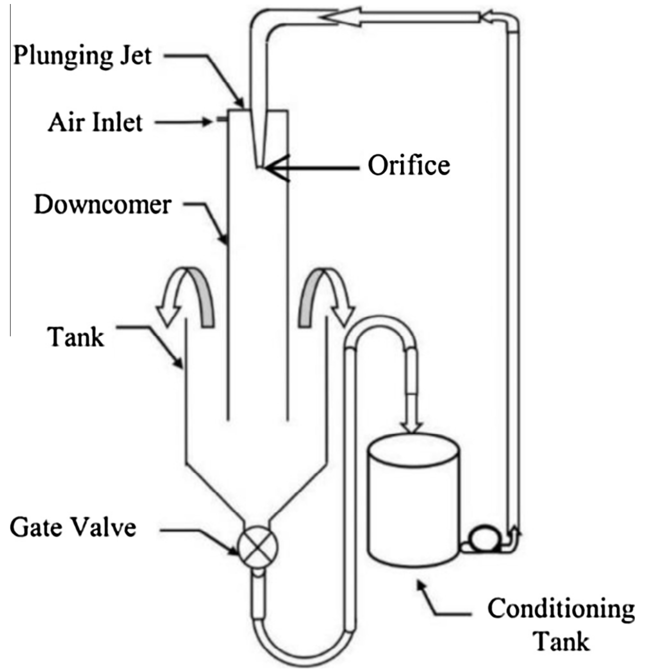

Fig. 1. Schematic view of the laboratory scale Jameson column flotation.

$$U_s = \left(\frac{U_G}{\varepsilon}\right) - \left(\frac{U_L}{1-\varepsilon}\right) = U_b\,(1-\varepsilon) \tag{1}$$

where U_s is slip velocity of air and water, U_G is gas superficial velocity, U_L is liquid superficial velocity implying the velocity if the volume rate flowed on its own through the cross section, considered separately from the other phase. U_b is the actual terminal velocity of a single bubble, and ε is the bubble void fraction in the liquid. This equation approximates a plug flow model for the two phase bubbly flow assuming a uniform distribution of single size bubbles over the cross section [31,11]. Richardson and Zaki [35] introduced Eq. (2) to solid-liquid systems and calculated the slip velocity. Wallis [42] and Clift et al. [11] showed experimentally that Eq. (2) is also valid for bubbles in the range of 100–500 μm in diameter. Hills [22] investigated that Eq. (2) was a good fit to the data achieved in a fairly uniform bubbling state observed only under low air flow rate conditions. He observed a net upwards liquid flow and a higher voidage at the center. It has been used more recently by Godfrey and Slater [19] to describe gas-liquid systems.

$$U_s = U_b(1-\varepsilon)^n. \tag{2}$$

Other researchers demonstrated a non-uniform voidage profile with a central maximum, which leads to gulf-streaming [37,38,22,14]. Shen and Finch [37,38] were able to monitor the air-liquid interface in an upward bubble column. The interface appeared due to sudden change in gas flow rate. The velocity of the interface was lowered due to hindrance effects brought about by an increase in the population of the bubbles representing a more realistic state for bubble swarm motion.

This research reports on the velocity measurements in a laboratory scale Jameson cell. It also demonstrates the numerically calculated average velocities of air and water. Improvements are made on the drift flux analytical model by incorporating radial gas hold-up profiles obtained from CFD modeling. Based on the laboratory system specifications, the slip velocity is calculated using the analytical model developed by Shen and Finch [37,38] for upward bubble columns. Finally, the data obtained from the analytical and numerical approaches are compared with those of experimental results to examine their validity.

2. Jameson cell

2.1. Experimental

Fig. 1 shows a schematic view of the laboratory scale column flotation device used. It comprises a down-comer of 50 mm diameter; a tank of 150 mm diameter and an orifice of 5 mm diameter that is at the end of the plunging jet and the length of the down-comer is 1824 mm. Water is pumped into the down-comer through the orifice creating a high-pressure jet within the down-comer, where intense contact between air bubbles and particles occurs. The air is self-induced by the Venturi effect and fine bubbles are consistently generated through imparting intense mixing. The bubbly mixture possesses high interfacial surface area which brings about rapid flotation and high throughput [12,4]. The tank, the external column shown in Fig. 1, ensures separation of bubbles from the liquid [5].

Experiments were conducted for the two phase flow of atmospheric air and water. The liquid inlet pressure was measured by a pressure gauge and at the same time the inlet air and liquid flow rates were measured using float style flowmeters. Fig. 2 shows the down-comer in its working state. The down-comer is an acrylic tube allowing full optical access as far as the intense bubble distribution allows; in the figure the two phase flow appears entirely turbid with the vast number of millimeter scale bubbles.