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Effects of particle size and concentration on bubble coalescence and froth formation in a slurry bubble column

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ABSTRACT

A new approach for simulating the formation of a froth layer in a slurry bubble column is proposed. Froth is considered a separate phase, comprised of a mixture of gas, liquid, and solid. The simulation was carried out using commercial flow simulation software (FIRE v2014) for particle sizes of 60–150 μm at solid concentrations of 0–40 vol%, and superficial gas velocities of 0.02–0.034 m/s in a slurry bubble column with a hydraulic diameter of 0.2 m and height of 1.2 m. Modelling calculations were conducted using a Eulerian–Eulerian multiphase approach with k–ε turbulence. The population balance equations for bubble breakup, bubble coalescence rate, and the interfacial exchange of mass and momentum were included in the computational fluid dynamics code by writing subroutines in Fortran to track the number density of different bubble sizes. Flow structure, radial gas holdup, and Sauter mean bubble diameter distributions at different column heights were predicted in the pulp zone, while froth volume fraction and density were predicted in the froth zone. The model was validated using available experimental data, and the predicted and experimental results showed reasonable agreement. To demonstrate the effect of increasing solid concentration on the coalescence rate, a solid-effect multiplier in the coalescence efficiency equation was used. The solid-effect multiplier decreased with increasing slurry concentration, causing an increase in bubble coalescence efficiency. A slight decrease in the coalescence efficiency was also observed owing to increasing particle size, which led to a decrease in Sauter mean bubble diameter. The froth volume fraction increased with solid concentration. These results provide an improved understanding of the dynamics of slurry bubble reactors in the presence of hydrophilic particles.

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Introduction

Slurry bubble column reactors have emerged as promising devices with a wide range of applications in the chemical and mineral industries. These reactors are widely used because of their simple design and low operating and maintenance costs. Furthermore, they have several advantages, including high mass transfer rates, isothermal conditions, and plug-free operation (Jamialahmadi, Zehtaban, Müller-Steinhagen, Sarrafi, & Smith, 2001; Jha, Raj Mohan, Chakraborty, & Meikap, 2008; Krishna, De Swart, Ellenberger, Martina, & Maretto, 1997; Li & Prakash, 1997). In recent decades, the hydrodynamic character of slurry bubble columns has attracted much attention and become the focus of multiphase flow reactor research (Ojima, Hayashi, & Tomiyama, 2014; Sarhan, Naser, & Brooks, 2016). In slurry bubble column reactors, the flow characteristics have a significant effect on performance. The ability to accurately predict the operating parameters that control the flow behaviour in multiphase systems is an essential part of any design or evaluation strategy.

As particles in slurry bubble column reactors play a critical role in the flow structure, extensive studies have been conducted into the effect of the presence of solid particles on the flow dynamics of slurry bubble column reactors (such as Ip, Wang, & Toguri, 1999; Krishna, Van Baten, & Ellenberger, 1998; Li & Prakash, 2000; Ojima et al., 2014; Rabha, Schubert, & Hampel, 2013; Rabha, Schubert, Wagner, Lucas, & Hampel, 2013b; Sarhan et al., 2016). Most of these published reports address the effects of particles with respect to the effect of solid concentration on the total gas holdup, revealing that the gas holdup decreases with increasing solid concentration. This was attributed to the presence of solid particles increasing the apparent viscosity of the liquid phase and promoting the bubble

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coalescence rate (Ojima, Sasaki, Hayashi, & Tomiyama, 2015; Rabha, Schubert, Wagner et al., 2013; Sarhan et al., 2016).

However, some contradictory studies have reported an increase in gas holdup with increasing solid concentration (Fan, Hemminger, Yu, & Wang, 2007; Jamialahmadi & Müller-Steinhagen, 1991; Kara, Kelkar, Shah, & Carr, 1982). For example, the presence of large solid particles (≤600 μm) in the system reportedly led to an increase in gas holdup (Fan et al., 2007). This increase was attributed to the presence of large particles in the system promoting the bubble breakup process. These contradictions are due to the different methodologies used in these studies to calculate the gas holdup. Furthermore, the size, concentration, and degree of wettability were not equally considered. Among previous experimental investigations, only a few studies addressed the effect of particle size on slurry bubble flow (Ojima et al., 2015; Rabha, Schubert, Wagner et al., 2013). Therefore, the effect of particle size on slurry bubble flow is not yet well understood.

Bubble coalescence in turbulent flows occurs when two gas bubbles collide, trapping liquid between them. The thickness of the trapped liquid decreases gradually to a critical thickness owing to drainage of the liquid before the film ruptures (Prince & Blanch, 1990). Models describing this process are based on two-phase systems (gas and liquid). However, the presence of solid in the inter-film can inhibit liquid drainage by steric obstruction. The effect of this obstruction depends on solid concentration, particle size, shape, and contact angle, and particle orientation at the interface (Ata, 2008). In our recent report (Sarhan et al., 2016), the effect of solid concentration and gas flow rate on gas holdup and Sauter mean bubble diameter in slurry bubble column was modelled. However, the presence of solid particles was not included in the bubble coalescence rate equation. Therefore, the objective of the current study is to incorporate the effect of solid particle presence into the bubble coalescence model. The influence of particle size (d_s), concentration (C_s), and gas flow rate (u_g) on the hydrodynamics of the slurry bubble column are predicted using commercial flow simulation software (FIRE v2014). The population balance equation for bubble breakup and bubble coalescence rate, and the interfacial exchange of mass and momentum, are included in the computational fluid dynamics (CFD) code using subroutines written in Fortran to track the number density of different bubble sizes. The model is validated using available experimental data (Ojima et al., 2014).

Materials and methods

Description of the simulated case

The slurry bubble column used in the present investigation is described in this section, and the operation conditions of the model and the properties of the fluid used for numerical simulation are introduced. The simulation was carried out in a slurry bubble column with a rectangular cross-section, with a column hydraulic diameter, D_H, of 200 mm (Ojima et al., 2014). The width, depth, and height of the column were 200, 200, and 1200 mm, respectively. The physical features of this slurry bubble column are shown in Fig. 1(a). Air and purified water were used as gas and liquid phase, respectively, and their property parameters remained constant in the simulations. Spherical silica gel particles (d_s = 60, 100, and 150 μm, ρ_p = 2250 kg/m^3) were used as the solid phase. The initial slurry height was 800 mm. The slurry was assumed to be perfectly mixed, which is reasonable for a small Stokes number. Gas was introduced into the system at the bottom of the slurry bubble column. The superficial gas velocities investigated in this study were 0.02 and 0.034 m/s. The particle volumetric concentration, C_s, was varied from 0 to 40 vol%. This specific geometry was used to validate CFD results in the slurry bubble column by comparing radial gas holdup profiles of the simulations with experimental data in an identical setup. Table 1 summarizes the hydrodynamic properties of dispersed phases and experimental conditions used in the present work. Computational grids of the slurry bubble column used in the present model are shown in Fig. 1(b).

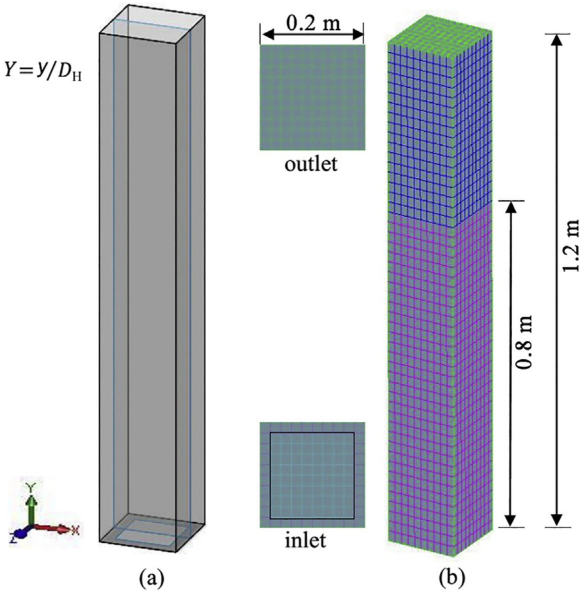

Fig 1. Computational domain used in the simulation of Ojima et al. (2014).

Table 1
Geometry and operation conditions used in the present simulation.

Column (width × depth × height) (mm)	200 × 200 × 1200
Initial liquid height (mm)	800
Gas phase	Air (ρ_g = 1.1 kg/m^3; μ_g = 0.00001 Pa s)
Liquid phase	Water (ρ_w = 998.713 kg/m^3; μ_w = 0.001 Pa s)
Solid phase	Silica gel (ρ_g = 2250 kg/m^3)
Temperature	20 °C
Pressure	Atmospheric pressure
Gas flow rate (m/s)	0.02, 0.034, 0.05
Solid concentration (vol%)	0, 10, 20, 30, 40
Particle size (μm)	50, 100

To obtain acceptable accuracy and affordable computational time, various grid independency tests were conducted with different mesh resolutions. Two different model grids were generated using the FAME Hexa meshing technique with a control volume of 5000 and 7000 cells, where each grid has a similar meshing scheme. The simulation was carried out on both grids using a superficial gas velocity of 0.034 m/sand a solid concentration of 10 vol% to predict the bubble velocity. The results of the grid independence test are shown in Fig. 2. No significant differences were observed in the results. Furthermore, the percentage error in the prediction of the bubble velocity for these two grid systems was within 2%. Therefore, the numerical solution was not considered sensitive to the number of cells and both grid systems were able to provide the same results. Therefore, the 5000-grid system was selected. The model setup is summarized in Table 2.

Mathematical model

The mathematical model for predicting four-phase hydrodynamics in the slurry bubble column is presented in this section. The present study treated gas, liquid, solid, and froth as four inde-

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