Chemical Engineering & Processing: Process Intensification 133 (2018) 40–57

Contents lists available at ScienceDirect

Chemical Engineering & Processing: Process Intensification

journal homepage: www.elsevier.com/locate/cep

Gas holdup and frictional pressure drop contributions in microstructured two-and three-phase bubbling bed with Newtonian and non-Newtonian liquids: Effect of coarse and fine particles with surface active agent

Ritesh Prakash*, Subrata Kumar Majumder*, Anugrah Singh

Department of Chemical Engineering, Indian Institute of Technology Guwahati, 781039, India

A R T I C L E I N F O

Keywords:
Gas holdup
Frictional pressure
Particle effect
Surfactant
Slurry column

A B S T R A C T

In the present work, experimental observations of the effect of coarse and fine particles, its concentration, and size on the gas holdup and frictional pressure drop with and without the presence of surfactants in a microstructured bubbling bed are reported. In-depth analysis of the effect of fine and coarse particles on gas holdup is performed. Frictional pressure drop and its component namely friction between fluid-wall, particle-wall, and fluid-particle are thoroughly investigated in two and three-phase systems. Five different particles (copper, zinc, alumina, silicon, and coal) of average particle size range (4.84 − 425 μm) and density range (1600 − 6310 kg/m^3) are used for the present experimental study. An empirical correlation is developed to predict gas holdup and frictional pressure drop at the wide range of experimental conditions. The developed correlation is able to predict the experimental data of gas holdup and frictional pressure drop within the error range of ± 20%.

1. Introduction

The gas sparged slurry column is one of the important multiphase contacting device, which is widely used in metallurgical, biochemical and chemical industries [1]. These industries frequently handle fluids like slurry, pulp mixture, wastewater, carboxymethyl cellulose solution, solid suspension, pulp, paper, gels, polymer solution, liquid crystals, etc. [2]. Many researchers have investigated the hydrodynamic characteristics of the circular and rectangular columns, but still, it is very complex to have a full understanding of the hydrodynamic behaviour [3–5]. The correct interpretation of hydrodynamic characteristic is imperative for appropriate design, optimization, scale-up, operation, analysis, modelling and control of a system, which improves the efficiency of the processing unit [6]. Construction of slurry columns are easy, but the scale-up process is tedious due to the scarcity of sufficient knowledge of hydrodynamic characteristics.

Many industrial columns are facing problems during the enhancement of product quality due to the considerable degree of backmixing of the slurry as well as that of dispersed gas phase, low interfacial area due to high coalescence rate, a short residence time of gas bubbles, non-homogeneous bubble size distribution, and uneven flow patterns. To counter these problems microstructured column can be used to minimize backmixing of gas and liquid phase, reduce channelling, provide homogeneous bubble size distribution, and low coalescence rate. The present work mainly focuses on the effect of coarse and fine particles on gas holdup and frictional pressure drop in the microstructured slurry column.

The gas holdup is defined as the ratio of the volume of the gas phase to the total volume of the column. It characterizes an integral value of all the bubble volumes in the system. It is one of the important hydrodynamic parameters in the scale-up process. Knowledge of gas holdup is necessary for estimation of the interfacial area, which governs the efficiency of the system. Variation of the gas holdup in the radial direction also affects the performance of the process. Mixing of phases in the system is also dependent on the radial variation of the gas holdup. Various parameters like the operating variables, geometric variables, and physical properties of the phases significantly affect the phase holdup characteristics of a system [3]. Li et al. [7] studied the effect of non-Newtonian fluid (Carboxymethyl cellulose) and sodium dodecyl sulfate (SDS) on the gas holdup. The investigation reported an increase of gas holdup with the increase in the superficial gas velocity and decrease with an increase of CMC concentration in the liquid. It was also reported that a mixture of CMC and SDS solution results in higher gas holdup than the air-water system. Anastasiou et al. [8] observed that gas holdup was decreased in presence of viscous solution which was due to the increase in coalescence behaviour of the gas bubbles. Mouza et al. [9] observed that the air-water and air-glycerine system resulted in almost the same gas holdup. However, little

* Corresponding authors.
E-mail addresses: ritesh.prakash@iitg.ernet.in (R. Prakash), skmaju@iitg.ernet.in (S. Kumar Majumder).

https://doi.org/10.1016/j.cep.2018.09.020
Received 28 May 2018; Received in revised form 20 September 2018; Accepted 25 September 2018
Available online 29 September 2018

Nomenclature

A_C	Cross-section area of the column (m^2)
b	Drift-flux model parameter (-)
C_s	Particle concentration (kg/m^3)
C_R	Ratio of (C_s /ρ_{sl}) (-)
C_0	Distribution parameter (-)
$C_{D,\ fl\text{-}p}$	Drag coefficient between fluid and particle (-)
D_R	Ratio of (d_p / h_m) (-)
d_p	Particle diameter (m)
d_b	Bubble diameter (m)
d_e	Equivalent column diameter (m)
d_c	Column diameter (m)
D_R	Ratio of (d_p/h_m) (-)
f_{sp}	Single-phase friction factor (-)
$f_{three\text{-}phase}$	Three-phase friction factor (-)
f_{p-w}	Particle-wall friction factor (-)
$f_{fl\text{-}w}$	Fluid-wall friction factor (-)
$f_{fl\text{-}p}$	Fluid-particle friction factor (-)
g	Acceleration due to gravity (m/s^2)
h_m	Gas-liquid-solid mixture height (m)
h_l	Clear slurry height (m)
H_R	Ratio of (h_m/d_c) (-)
k_1, k_2	Einstein constant (-)
K	Consistency index ($Pa.s^n$)
m_p	Mass of particle (kg)
n	Flow behaviour index (-)
n_i	Number of bubbles (-)
N	Total number of variables (-)
Re_t	Terminal Reynolds number (-)
Re_p	Particle Reynolds number (-)
$Re_{g\text{-}l}$	Gas-liquid mixture Reynolds number (-)
u_{sl}	Slurry velocity (m/s)
u_d	Drift velocity (m/s)
u_t	Terminal velocity (m/s)
$\bar{u}$	Average fluid velocity (m/s)
u_{sg}	Superficial gas velocity (m/s)
$u_{g\text{-}l}$	Actual fluid velocity of homogeneous gas-liquid mixture (m/s)
u_{sp}	Single phase velocity (m/s)
u_p	Particle velocity (m/s)
w_s	Slurry concentration (%)
STDEV	Standard deviation (-)
U	Standard uncertainty (-)
U_r	Relative uncertainty (-)
$\bar{x}$	Mean value of variables (-)
x_i	i^{th} components of variables (-)
Z	Axial length (m)

Greek Letter

$\alpha_{g\text{-}l}$	Volume fraction of gas in gas-liquid mixture only (-)
ϕ	Dispersed phase concentration by volume (-)
α_g	Gas holdup (-)
α_l	Liquid holdup (-)
α_s	Solid holdup (-)
μ_l	Liquid viscosity (Pa.s)
$\mu_{g\text{-}l}$	Gas-liquid mixture viscosity (Pa.s)
μ_{sl}	Slurry viscosity (Pa.s)
μ_{eff}	Effective viscosity (Pa.s)
σ_l	Surface tension of liquid (N/m)
σ_{sl}	Surface tension of slurry (N/m)
ρ_m	Mixture density (kg/m^3)
ρ_l	Density of liquid (kg/m^3)
ρ_s	Density of particle (kg/m^3)
ρ_{sl}	Slurry density (kg/m^3)
ρ_g	Density of gas (kg/m^3)
$\rho_{g\text{-}l}$	Density of gas-liquid mixture (kg/m^3)
ρ_{sp}	Density of single-phase (kg/m^3)
ΔP_T	Total pressure drop (Pa)
ΔP_h	Hydrostatic pressure drop (Pa)
ΔP_f	Frictional pressure drop (Pa)
ΔP_a	Pressure drop due to acceleration (Pa)
$\Delta P_{f,fl\text{-}p}$	Fluid-particle frictional pressure drop (Pa)
$\Delta P_{f,\ p-w}$	Particle-wall frictional pressure drop (Pa)
$\Delta P_{f,\ fl\text{-}w}$	Fluid-wall frictional pressure drop (Pa)
$\Delta P_{f,\ sp}$	Frictional pressure drop for single-phase flow (Pa)
$\Delta P_{f,\ three\text{-}phase}$	Frictional pressure drop for three-phase flow (Pa)
ΔL	Distance between pressure transducer (m)

enhancement was observed in the air-butanol system due to the reduction in the surface tension of the fluid.

The effect of particle concentration on gas holdup has been studied by many researchers. A decrease in gas holdup in presence of the solid particle (0 − 15% v/v) was also observed by Banisi et al. [10]. Vazirizadeh et al. [11] reported the effect of two different solid particles: quartz (hydrophilic) and talc (hydrophobic) on gas holdup and bubble size distribution in presence of the polyglycol surfactant. The presence of solid particles affects the gas holdup as; (i) it causes bubble breakup, hence gas holdup increases [12], (ii) increases coalescence behaviour of bubble which decreases gas holdup [10,13], (iii) it enhances bubble wake entrainment so gas holdup decreases [10], (iv) it increases the apparent viscosity of the fluids leading to a decrease in gas holdup [10,14], and (v) the particles attached to the bubble increases the weight of the bubble causing reduction in rising velocity leading to increase in the gas holdup [15,16]. The effect of the particles, particle size and particle concentration at the high gas temperature of a helium-water-alumina system was studied by Abdulrahman [17]. A decrease in gas holdup was observed by the addition of solid particles since the increase in slurry viscosity leads to promote the generation of substantial size gas bubbles while the breakup efficiency of the bubble reduces due to the reduction of instabilities at interfaces. Large bubbles have greater rise velocity and low residence time in the column which leads to the reduction of the gas holdup. It was also observed that the effect of a change in the particle size on gas holdup was negligible. According to Abdulrahman [17], the effect of particle size on the gas holdup was trivial. However, smaller particle size has a reasonably more gas holdup compared to the larger particle size [18]. The same effect was found in both the presence and absence of surfactants in the system. The effect of larger particles compared to the smaller is less significant because the smaller particles does not cause coalescence, but promote bubble breakup. According to Uribe-Salas et al. [19] the rise velocity of bubble-particle aggregate increases as the bubble size increases. Viscosity of the slurry increases by lowering the particle size at a certain slurry concentration due to attractive particle interaction [20–24]. Banisi et al. [10] illustrated that the solid loading also stabilizes the bubble wake and bubble swarm velocity due to increased viscosity of the slurry. It causes an increase in rising velocity of trailing bubbles due to inline bubble-bubble interaction. Kara et al. [25] performed the experiment in batch mode and observed a reduction of the gas holdup with an increase in solid concentration and particle size. There was no significant difference observed in gas holdup characteristics of air-water and air-water-solid system when the particle size of 10 μm was used. However, the three-phase system indicated slightly larger gas holdup than two-phase in presence of 10 μm particle. Khare and Joshi [26] analyzed the enhancement in gas holdup with an