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Single bubble behavior in gas–liquid–solid mini-fluidized beds

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HIGHLIGHTS

- Pressure drop strongly fluctuates in the fixed bed state in smaller bed.
- Obvious wall effect decreases the bubble size in MFBs under higher solid holdup.
- Suspension inertial force plays an important role in determining bubble size.
- The compressibility of gas phase and the bubble wake affect the bubble size.
- A correlation was developed to address the wall effect on the bubble size.

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ABSTRACT

Gas–liquid–solid mini-fluidized bed is a new and important reactor. However, the flow behavior in such a system is not well understood, even for the characteristics of single bubble. Initial fluidization, movement and size of singe bubble in three-phase co-current upward mini-fluidized beds of 2–10 mm sizes were studied with visual experiments. The results show that the variation of pressure drop across the bed with time is a strong fluctuation due to the coalescence of bubbles at lower superficial liquid velocities for smaller beds, while no obvious difference in the minimum fluidization velocity between the liquid–solid and gas–liquid–solid systems for a 10 mm MFB exists in the experimental ranges. The wall effect on the bubble size is dominant. The stronger wall effect decreases suspension inertial force, which leads to the diminution of bubble size. A force balance between the surface tension force and buoyant force dominates the bubble size in mini-bubble column at lower orifice gas velocities, while suspension inertial force plays more important role in governing the bubble size in three-phase mini-fluidized beds. Additionally, compressibility of the gas phase contributes to the variation in the bubble size; the bubble wake is observed even for such small solid particles, and can affect the following bubble size in smaller beds at relative high orifice gas velocities. An empirical equation was suggested to predict the bubble diameters in three-phase mini-fluidized beds.

1. Introduction

The gas–liquid–solid fluidized bed as one of the most important industrial operating units is extensively met in the areas of chemical, biochemical and environment engineering [1–5] and great efforts have been made to understand the fundamental knowledge of three-phase fluidized beds [6–11]. Bubble behavior plays a key role in determining the heat and mass transfer and overall efficiency of the bed and is mainly reflected by the bubble characteristics such as bubble size and rising velocity.

Single bubble behavior from an orifice submerged in a liquid–solid suspension is of fundamental importance, and relative studies have been reported even though most of them are for the bubble formation on the macro scale. Massimilla et al. [12] measured the single bubble volume in a three-phase fluidized bed and found that the bubble sizes in the presence of solid particles were larger than those in pure water, and increased with solid holdup. Yoo et al. [13] reported bubble sizes at pressurized condition decreased with an increase in system pressure and were independent of light polystyrene particles. Luo et al. [14] and Yang et al. [15] proposed a model to predict the bubble size in liquid–solid suspension at relatively wide range of pressure. The results based on this model indicated that the effect of the pressure on the bubble size was dominant at low pressures, and vice versa.

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Notation

Nomenclature

D_b	equivalent bubble diameter (m)
D_h	inner diameter of the mini-fluidized bed (m)
D_o	orifice diameter (m)
d_p	average size of particles (m)
g	gravitational acceleration (m/s^2)
H	fluidized bed height (m)
H_s	static bed height (m)
p	pressure (Pa)
S	standard values of deviation (m)
u_g	inlet orifice gas velocity (m/s)
U_g	superficial gas velocity (m/s)
u_l	liquid velocity (m/s)
U_l	superficial liquid velocity (m/s)
U_{mf}	minimum fluidization velocity for liquid–solid system (m/s)
U_{Lmf}	minimum fluidization liquid velocity for gas–liquid–solid system (m/s)
W_p	weight of particle (g)
ΔP_e	pressure drop across the empty bed (Pa)
ΔP_t	total pressure drop (Pa)
ΔP_p	pressure drop across the solid particle bed (Pa)

Greek letters

ε	voidage (–)
ρ	density (kg/m^3)
μ	viscosity (Pa s)
Φ	particle sphericity (–)
σ	surface tension (N/m)
γ	contact angle (°)

Dimensionless group

Ca	Capillary number, $Ca = u\mu/\sigma$
Re	Reynolds number, $Re = \rho u D_h/\mu$
We	Weber number, $We = \rho u^2 D_b/\sigma$

Subscripts

b	bubble
l	liquid phase
p	solid particles

Recent researches indicated that gas–liquid and liquid–liquid flows in mini- and micro-channels show excellent interfacial contact ability and higher mass and heat transfer rates [16–20]. Inspired by the miniaturization of chemical reactors, studies on the fluidized beds are gradually evolving from macro to micro scales. Since Funazukuri et al. [21] put forward a concept of micro-fluidized beds in 1984, many researches have been focused on the miniaturized fluidized beds [22–26]. Potic et al. [22] investigated the flow regime and bed expansion characteristics of gas–solid fluidized beds with an internal diameter of a few millimeters by visual inspection under high pressure and temperature conditions. The increase of minimum fluidization and bubbling velocities (U_{mf} and U_{mb}) with the decrease of the fluidized bed diameter for gas–solid system were observed by researchers [23,25,27], which were contributed by the wall effect. For liquid–solid system, Doroodchi et al. [28] examined the wall effect on the hydrodynamic characteristics in capillary tubes in terms of pressure drop. The bed voidage sharply increased with the decrease of bed diameter, which caused a reduction of the pressure drop across the bed, and a pressure drop overshoot appeared at smaller beds due to wall friction. Zivkovic et al. [29,30] reported the liquid–solid fluidization behavior in a rectangular micro-channel of 400 μm × 175 μm and concluded that the surface force was responsible for the successful fluidization. As a promising reactor, the miniaturized fluidized beds show a broad application prospect [31,32]. In addition, micro-structure fluidized membrane reactors [33,34] and supercritical water micro-fluidized beds [35] have also been proposed.

For gas–liquid–solid system, the bubble behaviors will affect the flow and mass and heat transfer characteristics of three-phase mini-fluidized beds (MFBs). However, no studies on the bubble behavior in MFBs were presented to our knowledge. In the similar microfluidic gas–liquid or liquid–liquid systems, numerous researches have contributed to the bubble or drop formation and control [36–41]. Gaestecki et al. [37] found that the bubble size was related to the gas or liquid velocity. There was only flow rate ratio of gas and liquid phase in their formula. Thorsen [42] emphasized the effect of shear stress on the bubble size, and the bubble length was shown as a power-law function with Capillary number. Yang et al. [43] simulated on the droplet formation behavior in a T-shaped micro-fluidic device using lattice Boltzmann method. They analyzed in detail the pressure variations of the continuous and dispersed phases along with the flow dynamics in different regimes, i.e., squeezing regime, dipping regime and jetting regime. For gas–liquid–solid flow on the micro scale, the effect of solid particles on the bubble behavior in the micro-channel was numerically simulated with the solid holdup ranging from 0.3% to 8% in our previous study [44]. The results showed that the bubble was formed under the squeezing pressure and the bubble volume was related to some factors such as gas and liquid velocities, solid properties and wall conditions. The presence of solid particles increased the apparent viscosity of liquid phase. Hence, the detachment time and bubble length in liquid–solid flow were shorter than that in liquid flow.

From the above analyses, it can be seen that when the bed diameter decreases to the millimeter or even micrometer scale, wall effect on flow properties is prominent. Although several investigations on mini- and micro-scale fluidization behavior in two-phase systems have been made, no such a study on three-phase fluidization system was found in open literature. Bubble characteristics such as bubble size in gas–liquid–solid MFBs may be different from that in the macro-scale fluidized beds due to the wall effect, and may have significant influence on the bubble wake, which is essential to study in order to propose a basis for designing gas–liquid–solid MFBs.

The primary objective of this study is to study the flow characteristics especially the bubble behavior in gas–liquid–solid MFBs. The outline of the work is as follows. Firstly, U_{mf} and flow regime were preliminarily investigated. Secondly, single bubble formation was monitored. Thirdly, various factors relating to the single bubble size in the mini-bubble column were analyzed. Finally, bubble sizes were studied and a correlation was proposed to predict the bubble sizes in gas–liquid–solid MFBs.

2. Experimental

The experimental apparatus of gas–liquid–solid MFB is illustrated in Fig. 1. All MFBs were fabricated with polymethyl methacrylate (PMMA) by precision milling. Such MFB consists of two fluid inlets, a liquid pre-distribution, a liquid distributor (a wire mesh), a mini-fluidized bed, a disengagement section and fluid outlet.