Phase Holdup Characteristics of Viscous Three-Phase Inverse Fluidized Beds

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Received May 11, 2007; Accepted August 31, 2007

Abstract: Characteristics of individual phase holdup and bed porosity were investigated in viscous three-phase inverse fluidized beds, the diameter of which was 0.152 m (ID) and the height was 2.5 m. The effects of the gas and liquid velocities, particle density (kind), and liquid viscosity on the individual phase holdups, such as gas, liquid, and solid holdups, and the bed porosity were determined. The gas holdup increased with increasing gas or liquid velocity or particle density, but decreased with increasing liquid viscosity. The value of the liquid holdup increased with increasing liquid viscosity, whereas, the effects of the gas and liquid velocities on the liquid holdup were somewhat complicated. The value of the solid holdup decreased with increasing gas or liquid velocity or liquid viscosity. The solid holdup in the beds of relatively-low-density particles exhibited a higher value than that in the beds of relatively-high-density particles. The bed porosity increased with increasing gas or liquid velocity or liquid viscosity. The values of the individual phase holdups and bed porosities correlated well in terms of the operating variables.

Keywords: phase holdup, bed porosity, viscous liquid medium, three-phase, inverse fluidized bed

Introduction

Practical applications of three-phase (gas-liquid-solid) fluidized beds have been increased because of their unique advantages, such as high heat and mass transfer rates, low pressure drops, simple operation, convenient scheme for continuous operation, low operating costs and high contacting efficiency between different phases [1-4]. However, in biochemical, food, and environmental processes, fluidized solid materials are usually small, porous, and light; therefore, usage of conventional three-phase fluidized beds has been restricted because the media materials (such as absorbent, adsorbent, catalyst, or medium) frequently float in the continuous liquid medium owing to the lower density of these materials relative to that of the liquid medium [5,6].

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To overcome the disadvantages of the three-phase fluidized bed, a three-phase inverse fluidized bed has been proposed to reasonably, fluidize those low-density materials where the materials can be fluidized by means of a downward flow of the continuous liquid medium. Several investigations have been performed using three-phase inverse fluidized-bed reactors or contactors. The hydrodynamic characteristics, such as the bubble properties, flow regime, bed expansion, minimum liquid fluidization velocity, and transition velocity for the uniform fluidization, have been examined [7-14]. Gas-liquid and liquid-solid mass transfer, liquid mixing, and heat transfer in three-phase inverse fluidized beds have been also studied for the more practical applications in industrial processes [15-22].

The wastewater samples with floating material and liquid phase in the biochemical, pulp, and food processes are generally viscous. In addition, low-density suspension materials are frequently encountered in those pro-
Table 1. Properties of the Solid Materials Used in This Study

<table>
<thead>
<tr>
<th>Particle</th>
<th>Shape</th>
<th>Average diameter</th>
<th>Density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polypropylene</td>
<td>Spheres</td>
<td>4 mm</td>
<td>877.3</td>
</tr>
<tr>
<td>Polyethylene</td>
<td>Spheres</td>
<td>4 mm</td>
<td>966.6</td>
</tr>
</tbody>
</table>

Experiments

Experiments were performed in an acrylic column of 0.152 m in diameter and 2.5 m in height, as shown in Figure 1 [12,21,22]. A perforated plate, which contained 237 evenly spaced holes, each with a diameter of 3 mm, served as a liquid distributor with a stainless-steel screen of 300 mesh. The liquid distributor was installed at the top of the main column. The liquid phase was introduced to the liquid calming section through a 2.54 cm pipe from the liquid reservoir. The liquid distributor was situated between the main column section and a stainless-steel box, from which the liquid phase was withdrawn downward. At the bottom, the gas was fed to the column through four evenly spaced 0.63 cm distributor pipes that contained 28 holes of 1 mm diameter.

The flow rates of the gas and liquid phases were measured by flow meters and regulated by means of globe valves on the feed and bypass lines. A cartridge heater (2.54 cm-OD × 1.5 m-long) was installed vertically at the center of the bed to maintain the temperature in the bed at a given level (25 ± 0.5 °C). The temperatures in the fluidized-bed were measured by eight iron-constantan thermocouples (J-type) that were mounted at the center between the heater and the column at 0.15 m height intervals from the liquid distributor.

Twelve pressure taps were mounted flush with the wall of the column at 0.125 m height intervals from the liquid distributor. The extended bed height was taken as the point at which a change in the slope of the pressure drop plot was observed [2,3]. Individual phase holdups and bed porosity were determined by means of the static pressure drop method from knowledge of the pressure drop, bed height, and properties of the gas, liquid, and solid [1-5,21,22]. Throughout this study, aqueous solutions of Carboxy Methyl Cellulose (CMC), the apparent viscosities of which were varied from 1.0 to 38.0 × 10⁻³ Pa.s, were used as the continuous liquid phase, compressed filtered air was the gas phase, and either polyethylene (PE) or polypropylene (PP) beads, with a density of 966.6 or 877.3 kg/m³, respectively, were used as the solid phase. The contact angle of each particle with water was measured using an Erma contact angle meter (model G-1, Japan). The contact angle of PP was 84° and that of PE was 85°. The apparent viscosity of the liquid phase was determined with a Brookfield Synchroelectric Rotational Viscometer [18,23]. The properties of the solid materials and the liquid phase with respect to the fluid flow rate range are summarized in Tables 1 and 2, respectively.
Phase Holdup Characteristics of Viscous Three-Phase Inverse Fluidized Beds

Table 2. Liquid Physical Properties and Fluid Flow Rate Ranges

<table>
<thead>
<tr>
<th></th>
<th>$\mu_{L,app} \times 10^3$ (Pa.s)</th>
<th>$\sigma_L \times 10^3$ (N/m)</th>
<th>$\rho_L$ (kg/m$^3$)</th>
<th>$U_G \times 10^2$ (m/s)</th>
<th>$U_L \times 10^2$ (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure water</td>
<td>0.96</td>
<td>72.9</td>
<td>1000</td>
<td>0.05 ~ 0.8</td>
<td>1 ~ 5</td>
</tr>
<tr>
<td>Aqueous solution of CMC (0.1 wt%)</td>
<td>11</td>
<td>73.2</td>
<td>1001</td>
<td>0.05 ~ 0.8</td>
<td>1 ~ 5</td>
</tr>
<tr>
<td>Aqueous solution of CMC (0.2 wt%)</td>
<td>24</td>
<td>73.3</td>
<td>1002</td>
<td>0.05 ~ 0.8</td>
<td>1 ~ 5</td>
</tr>
<tr>
<td>Aqueous solution of CMC (0.3 wt%)</td>
<td>38</td>
<td>73.6</td>
<td>1003</td>
<td>0.05 ~ 0.8</td>
<td>1 ~ 5</td>
</tr>
</tbody>
</table>

Figure 2. Effect of gas velocity on the individual phase holdups in viscous three-phase inverse fluidized beds (Particle: Polyethylene; $\rho_S = 966.6$ [kg/m$^3$]; $\mu_L = 11 \times 10^{-3}$ [Pa.s]).

Figure 3. Effect of gas velocity on the individual phase holdups in viscous three-phase inverse fluidized beds (Particle: Polyethylene; $\rho_S = 966.6$ [kg/m$^3$]; $\mu_L = 24 \times 10^{-3}$ [Pa.s]).

Results and Discussion

The individual phase holdups in three-phase inverse fluidized beds with a viscous liquid medium can be seen in Figures 2 and 3, respectively, when the fluidized solid material was polyethylene ($\rho_S = 966.6$ kg/m$^3$). In these Figures, the gas holdup increases and the solid holdup decreases with increasing gas velocity in all of the cases studied. However, the variation of liquid holdup with the variation of gas velocity was somewhat complicated. That is, in the relatively low range of liquid velocities ($U_L = 0.01 ~ 0.02$ m/s), the liquid holdup increases with increasing gas velocity, whereas in the relatively high liquid velocity range ($U_L = 0.03 ~ 0.05$ m/s), the val-
Figure 4. Effect of gas velocity on the individual phase holdups in viscous three-phase inverse fluidized beds (Particle: Polypropylene; $\rho_s = 877.3$ [kg/m$^3$]; $\mu_L = 11 \times 10^{-3}$ [Pa.s]).

The value of the liquid holdup exhibits a local maximum with increasing gas velocity. The reason why the liquid holdup increases gradually with increasing gas velocity could be due to the fact that the bed can expand with increasing gas velocity in a given liquid velocity. In the relatively low range of liquid velocities, the hindrance effects of the liquid flow on the rising bubble would be relatively small; thus, the increment of gas holdup is not high with increasing gas velocity. However, in the relatively high range of liquid velocities, the impact from liquid flowing downward on the rising bubbles can be significant with increasing gas velocity; thus, the increment of gas holdup becomes significant and, therefore, the liquid holdup decreases to compensate for the increased gas holdup. Therefore, the liquid holdup shows a local maximum with increasing gas velocity at a given liquid velocity.

For beds of relatively light polypropylene particles ($\rho_s = 877.3$ kg/m$^3$), typical examples of individual phase holdups can be seen in Figures 4 and 5. In these Figures, the gas and liquid holdups increase, but the solid holdup decreases, in every case with increasing gas velocity. As the gas velocity increases, the bed expands; thus, the gas and liquid holdups increase, which results in the decrease of the solid holdup in the bed. Note in these Figures that the value of solid holdup in the beds of the polypropylene particles is somewhat higher than that of the polyethylene particles. This phenomenon could be due to the fact that the density of the former is smaller than that of the latter. It is known that the beds of relatively light particles cannot be easily expanded in three-phase inverse fluidized beds because of buoyance forces acting on the particles [5,6]. Therefore, the values of the gas and liquid holdups are somewhat smaller in the beds of relatively light particles than they are for relatively heavy particles.

Figure 5. Effect of gas velocity on the individual phase holdups in viscous three-phase inverse fluidized beds (Particle: Polypropylene; $\rho_s = 877.3$ [kg/m$^3$]; $\mu_L = 38 \times 10^{-3}$ [Pa.s]).
Phase Holdup Characteristics of Viscous Three-Phase Inverse Fluidized Beds

The effect of the liquid velocity on the individual phase holdups in viscous three-phase inverse fluidized beds can be seen in Figure 6. In this Figure, the values of the gas and liquid holdups increase gradually with increasing liquid velocity. This behavior was expected because the liquid flows downward to fluidize the low-density particles against the buoyance force acting on the particles. In addition, the downward flow of the liquid phase can interfere with the upward flow of gas bubbles, which will exit from the bed; thus, the gas holdup increases with increasing liquid velocity. The solid holdup decreases with increasing liquid velocity, as can be seen in Figure 6, to compensate for the increased gas and liquid holdups in the beds.

The effect of the liquid viscosity on the individual phase holdups in three-phase inverse fluidized beds can be seen in Figure 7. In this Figure, the gas holdup decreases with increasing liquid viscosity. It has been reported that the bubble size increases in conventional and inverse fluidized beds with increasing liquid viscosity [1-3,5]. Thus, the rising velocity of bubbles increases with increasing liquid viscosity, because the rising velocity of bubbles is proportional to the bubble size. Therefore, the gas holdup decreases with increasing liquid viscosity, as in the case of conventional three-phase fluidized beds [23]. In Figure 7, the liquid holdup increases, but the solid holdup decreases, with increasing liquid viscosity. Note that the effect of the liquid viscosity on the solid holdup diminishes with increasing liquid velocity in the range 0.03 ~ 0.05 m/s, in the beds of relatively heavy particles ($\rho_S = 966.6 \text{ kg/m}^3$)

However, in the beds of relatively light particles ($\rho_S = 877.3 \text{ kg/m}^3$), the effect of the liquid viscosity on the gas, liquid, and solid holdups is considerable, as can be seen.
in Figure 8, where the gas and solid holdups decrease, but the liquid holdup increases, with increasing liquid viscosity. The bed could be expanded more easily, mainly by increasing the liquid holdup with increasing liquid viscosity. It has also been reported that the liquid holdup increases with increasing liquid viscosity in conventional three-phase fluidized beds [1-3].

The increasing trends of the bed porosity with increasing gas velocity and liquid viscosity in the beds of heavy and light particles can be seen Figures 9 and 10, respectively. As mentioned earlier, the inverse fluidized bed can be expanded by increasing the gas or liquid velocity or liquid viscosity, which consequently results in the increased bed porosity, as in the cases of conventional three-phase fluidized beds.

The values of the gas and liquid holdups and the bed porosity correlated well in terms of the operating variables when using Eqs. (1), (2), and (3), respectively, with correlation coefficients of 0.963, 0.904, and 0.931, respectively. The ranges of the gas and the liquid velocities and the liquid viscosity were 0.0005 m/s ≤ \( U_G \) ≤ 0.008 m/s, 0.01 m/s ≤ \( U_L \) ≤ 0.05 m/s, and 0.96 mPas ≤ \( \mu_L \) ≤ 38 mPas, respectively.

\[
\varepsilon_G = 5.517 \left( U_G \right)^{0.383} \left( U_L \right)^{0.426} \left( \mu_L \right)^{-0.071} \left( \frac{\rho_S}{\rho_L} \right)^{11.357} \tag{1}
\]

\[
\varepsilon_L = 4.014 \left( U_G \right)^{0.136} \left( U_L \right)^{0.155} \left( \mu_L \right)^{0.056} \left( \frac{\rho_S}{\rho_L} \right)^{2.009} \tag{2}
\]

\[
\text{bed porosity} = 5.568 \left( U_G \right)^{0.158} \left( U_L \right)^{0.169} \left( \mu_L \right)^{0.048} \left( \frac{\rho_S}{\rho_L} \right)^{2.762} \tag{3}
\]
Conclusion

Some significant conclusions can be drawn from the results of this study. The individual holdups of the gas, liquid, and solid phases were determined by means of the static pressure drop method in three-phase inverse fluidized beds with a viscous liquid medium. The gas holdup increased with increasing gas or liquid velocity, but decreased with increasing liquid viscosity. The value of the liquid holdup increased generally with increasing gas or liquid velocity or liquid viscosity. The solid holdup decreased generally with increasing gas or liquid velocity or liquid viscosity. The bed porosity increased with increasing gas or liquid velocity or liquid viscosity in three-phase inverse fluidized beds with a viscous liquid medium.

The values of the gas and liquid holdups and the bed porosity correlated well in terms of the operating variables within these experimental conditions:

\[
\varepsilon_G = 5.517 \left( U_G \right)^{0.383} \left( U_L \right)^{0.426} \left( \frac{\rho_S}{\rho_L} \right)^{-0.071} \left( \frac{\mu_L}{\rho_L} \right)^{11.357}
\]

\[
\varepsilon_L = 4.014 \left( U_G \right)^{0.136} \left( U_L \right)^{0.155} \left( \mu_L \right)^{0.056} \left( \frac{\rho_S}{\rho_L} \right)^{2.109}
\]

\[
1 - \varepsilon_S = 5.568 \left( U_G \right)^{0.158} \left( U_L \right)^{0.169} \left( \mu_L \right)^{0.048} \left( \frac{\rho_S}{\rho_L} \right)^{2.702}
\]

Nomenclature

- \( U_G \): gas velocity (m/s)
- \( U_L \): liquid velocity (m/s)

Greek letters

- \( \varepsilon_G \): gas holdup
- \( \varepsilon_L \): liquid holdup
- \( \varepsilon_S \): solid holdup
- \( \mu_L \): liquid viscosity (Pa.s)
- \( \rho_L \): liquid density (kg/m\(^3\))
- \( \rho_S \): solid density (kg/m\(^3\))
- \( \sigma_L \): liquid surface tension (N/m)

References