AXIAL DISTRIBUTION OF SOLID HOLDUPS IN BINARY SOLIDS CIRCULATING FLUIDIZED BEDS

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The hydrodynamic behavior of binary solids circulating fluidized beds was examined in terms of axial distributions of apparent solid holdup as well as of fine and coarse solid holdups. Experiments were carried out in two circulating fluidized beds of 3 m in height and 97 mm and 150 mm in diameter, using FCC catalysts with a mean diameter of 69.7 μm as the fine particles and 321-μm silica sand and 633-μm activated alumina as coarse particles. The influences of gas velocity, solids circulation rate, loading ratio of coarse particles and bed diameter on the axial distributions of apparent holdup and of fine and coarse particles holdups were investigated. Comparisons were made of the axial distributions of solids holdups both in the presence and absence of coarse particles. It was found that the addition of coarse (or dense) particles results in a significant variation in both the apparent and the fine particles holdups. In addition, the nonuniformity of the axial solid holdup distribution was found to vary with increasing loading ratio of coarse particles.

Introduction

Due to high heat and mass transfer rates and the ability to control the residence time of circulating particles, the MSFB (multi-solid fluidized bed) or MPTB (multi-solid pneumatic transport bed) is of particular interest for combustion and gasification of coal, petroleum coke, wood, and solid wastes. The potential application of such a reactor in catalytic exothermic reactions is also being developed. A conventional MSFB or MPTB is a fluidized bed in which a circulating bed of fine particles (50 to 500 μm in size) is superimposed on a bubbling bed of coarse particles (1 to 15 mm in diameter). Several studies of the hydrodynamic features of MSFB or MPTB have clearly demonstrated that due to the interaction of fine particles, large particles and gas, the flow behavior is very complex and not directly translatable from a single solid fluidized bed system. For example, the increase in the amount of holdup of fines and carryover of coarse particles as well as particle segregation would be observed in a MSFB. It is clear, however, that the information about the axial particle segregation and the variations of apparent solid holdup and of fine and coarse particle holdups in multi-solids CFB are still insufficient for proper design and operation. In addition, the bubbling bed operation and the coarse particle sizes in the conventional MSFB or MPTB are not in our interest to develop a gas catalytic reactor system without the formation of gas bubbles.

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Therefore, it is the aim of the present work to measure the axial distributions of apparent solid holdup as well as fine and coarse particle holdups in binary solids circulating fluidized beds under a wide range of operating conditions. A comparison is made of the axial distributions of solids holdups for various operating conditions in two circulating fluidized beds in the presence and absence of coarse particles. The results obtained in the experiments are used to clarify the flow mechanism of binary solids CFB, which is believed to provide a fundamental foundation for reactor modeling.

1. Experimental Apparatus and Procedure

The schematic diagram of experimental apparatus employed in this study is illustrated in Fig. 1. The particles are entrained in the upward-flowing stream along a riser, 97 mm or 150 mm in diameter and 3.0 m in height, and exit at the top through a smooth exit bend into a cyclone system. The particles are collected from the gas by the cyclone system at the top of the riser and then fed back to the riser by means of a U-valve located at the bottom of a bubbling fluidized bed of 105 mm diameter that also serves as a particle storage hopper. The solids circulation rate is controlled by adjusting the flow rate of aeration air at the injecting points of the U-valve, and is measured by diverting solids into a measuring tank for a known time.

All the experiments were carried out at ambient temperature and pressure with air as the fluidizing gas.
The fine particles used were FCC catalysts with a mean diameter of 69.7 μm, while the coarse particles were silica sand and activated alumina with mean diameters of 321 μm and 633 μm, respectively. The properties of the particles used in the experiments are shown in Table 1. The gas velocity and solids circulation rate were in the range of 1.0 to 4.5 m/s and 1.0 to 130 kg/m²s. In all the experiments, the height of the solids in the storage bubbling bed was carefully fixed at 1.7 m. The axial apparent solids holdup profile was determined by measuring the pressure differences along the riser by means of a pressure sensor which was connected to pressure taps installed along the riser wall, i.e.,

\[- \frac{dP}{dz} = \rho_p (1 - \varepsilon) g \]  

(1)

where \( \rho_p \), the apparent solids density, was estimated by the following equation.

\[ \rho_p = \rho_s \rho_{ps} \{1 - x_v\} \rho_{ps} \]  

(2)

To obtain the cross-sectionally averaged fraction of coarse particles (which will be referred to as fraction of coarse particles in this paper), \( x_c \), the isokinetic sampling method seems appropriate, although it is tedious. As the local velocities of both fine and coarse particles were unknown, sampling could not be made under isokinetic conditions. However, as a first approximation, we attempted to obtain the fraction of coarse particles, \( x_c \), by sucking samples from taps installed at the bed wall. After sieving, the fraction of coarse particles was determined.

To confirm the accuracy of this sampling method, the axial profile of \( x_c \) was integrated numerically from \( z = 0 \) to \( z = H \) in the following way.

\[ x_{c,ave} = \frac{1}{H} \int_0^H (1 - \varepsilon) x_c \, dz \]

(3)

According to the principle of mass balance, the value of \( x_{c,ave} \) should be identical to the value of \( x_c \) at any operating condition. Comparison between \( x_{c,ave} \) and \( x_c \) for all the experiments has been made and a relative deviation of ±20% was found.

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Table 1. Properties of particles used in the present experiments

<table>
<thead>
<tr>
<th>Items</th>
<th>( d_p (\mu m) )</th>
<th>( \rho_s (kg/m^3) )</th>
<th>( U_s (m/s) )</th>
<th>Geldart’s Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>FCC</td>
<td>69.7</td>
<td>1702</td>
<td>0.249</td>
<td>A</td>
</tr>
<tr>
<td>Silica Sand (SS)</td>
<td>321</td>
<td>2644</td>
<td>2.63</td>
<td>B</td>
</tr>
<tr>
<td>Activated Alumina (AA)</td>
<td>633</td>
<td>1271</td>
<td>3.28</td>
<td>B</td>
</tr>
</tbody>
</table>

Fig. 2 Axial distribution of apparent, fine and coarse particles holds and gas velocity of 1.5 m/s (Solids: SS/FCC, \( x_{0} = 0.2, D = 0.097 m \))

Based on the above measurements, the axial profiles of the coarse and fine particle holds can be therefore calculated as follows with an estimated error of less than ±5%.

\[ 1 - \varepsilon_c = x_c (1 - \varepsilon) \]  

(4)

\[ 1 - \varepsilon_f = (1 - x_c) (1 - \varepsilon) \]  

(5)

2. Results and Discussion

2.1 The effects of gas velocity and solids circulation rate

Figure 2 shows the typical results of apparent, fine and coarse solids holds in the riser in the presence of silica sand coarse particles at a relatively low gas velocity (\( U_s = 1.5 m/s \)). Experimentally, it is observed that at a low gas velocity which is fairly smaller than the terminal velocity of a single coarse particle (as listed in Table 1), the coarse particles are retained in the riser. In this case, the bed is composed of a dense region in the bottom section containing coarse and fine particles, and a dilute region in the upper section containing only fine particles. This is very similar to what is observed in a conventional MSFB 2,11. With an increase in the solids circulation rate, the coarse particles are partially entrained by the gas and the fine particles stream, and eventually carried out of the riser. As a result, the height of the dense region of the coarse particles moves upward and the holds decrease in the bottom section and increase in the upper section. As the solids circulation rate is further increased, the coarse particles are entirely circulated. On the other hand, when the circulation rate of the fine particles reach or go beyond the saturated carrying capacity corresponding to the gas velocity, an S-shaped profile in both the apparent and fine solids holds is probably formed due to the accumulation of
fine particles at the bottom section of the bed, as shown in Figs. 2 (a) and (b).

When the gas velocity approaches the terminal velocity of a single coarse particle, as shown in Fig. 3 ($U_g = 2.5 \text{ m/s}$), both coarse and fine particles are carried out of the riser. In this case, if the solids circulation rate is quite low, the profiles of exponential form will be exhibited in the apparent, coarse and fine particles holdup profiles, due to the acceleration of particles and the friction between the particles and the riser wall. With increasing solids circulation rate, the coarse particle fractions tend to show a uniform axial distribution due to the fully entrained flow. However, the amount of the fine particles retained in the riser, particularly at the bottom section, are increased. If the solids circulation rate is increased and finally goes beyond the saturated carrying capacity, as described earlier, S-shaped profiles in apparent and fine particles holdup can be observed again due to the accumulation of fine particles at the bottom section of the riser (see Fig. 3 (a, b)).

At a higher gas velocity which is larger than the terminal velocity of a single coarse particle (Fig. 4, $U_g = 3.0 \text{ m/s}$), uniform axial distributions in the coarse particle fraction are always observed in the range of solids circulation rates used in this work, as shown in Fig. 4 (c). This means that both the fine and coarse particles are fully entrained and recycled at high gas velocity. In this case, if the solids circulation rate is increased, the apparent and fine particles holdups will increase, and their distributions along the bed height will become pronounced (Fig. 4 (a, b)).

2.2 Effect of the loading ratio of coarse particles

Figures 5 and 6 show the axial profiles of apparent and fine particles holdups as a function of loading ratio of coarse particles. This loading ratio varied from 0 (i.e., without coarse particles) to 40% (i.e., with coarse particles). It is seen from Fig. 5 (a) that, for a gas velocity of 1.5 m/s and a solids circulation rate of 8 kg/(m²s), the apparent solids holdup in the riser with coarse particles ($x_{c0} = 0.05$ and 0.2) is smaller than that in the riser without coarse particles ($x_{c0} = 0$). However, with increasing $x_{c0}$, the apparent solids holdup becomes larger and then goes beyond that in the riser without coarse particles. At the same time, a decrease in fine solids holdup is observed in the presence of coarse particles, as shown in Fig. 5 (b). In contrast, at a gas velocity of 3.0 m/s and a solids circulation rate of 70 kg/(m²s), the riser with coarse particles yields higher apparent solids holdup than that in the absence of coarse particles (see Fig. 6 (a)), whereas an increased fine solids holdup at lower $x_{c0}$ and a decreased fine solids holdup at higher $x_{c0}$.
are obtained (see Fig. 6 (b)). Such extreme variations in both the apparent and fine solids holdups are believed to be the result of interactions between the gas and particles and between particles. Generally, it is easy to understand that the presence of coarse particles would appreciably slow down the movement of fine particles in the bed, due to the increase in the extent of interaction between the fine and coarse particles (e.g., collision and aggregation) which may result in considerable backmixing and downflow in the wall region. Consequently, the solids holdup increases with increasing loading ratio. On the other hand, because of the presence of coarse particles, the fine particles would also move faster due to the increasing interstitial gas velocity resulting from the decrease in the effective cross-sectional area of flow. This will naturally result in a decrease in solids holdup. It is now clear that the variation of solids holdup with the loading ratio will depend significantly on the equilibrium of the above two adverse effects. The experimental results obtained in this study, as described above, confirm that when a bed is operated at relatively low gas velocities and solids circulation rates, the extent of increase in the fine solids holdup due to the interaction between fine and coarse particles is smaller than the extent of the decrease in fine solids holdup due to the increased fine particle velocity caused by an increase of interstitial gas velocity. Consequently, the fine particle holdup would decrease in the riser with coarse particles. However, with increasing $x_{C0}$, the bed gradually yields a large interaction between fine and coarse particles and hence an increase in both $1-\varepsilon$ and $1-\varepsilon_f$. At $x_{C0} = 0.4$, due to the considerable increase in the amount of coarse particles, $1-\varepsilon$ in the binary solids system becomes larger than that in only fine solids system. At high gas velocities and solids circulation rates, when $x_{C0}$ is low, the effect of particle interaction has a dominant effect, hence the observed increases in apparent and fine solids holdups, while decreases in both the $1-\varepsilon$ and $1-\varepsilon_f$ occur when $x_{C0}$ is further increased because the effect of increase in fine particles velocity tends to gain dominance over the particle interaction.

### 2.3 Effect of bed diameter

Comprising the axial distributions of apparent and fine solid holdups for the riser of 97-mm diameter and that of 150-mm diameter, as plotted in Figs. 7 and 8, however, indicate that under the same operating conditions the apparent and fine solids holdups are both increased at the bottom section and decrease at the upper section for a larger bed diameter. This may have contributed to the enhancement of the effect of solid downflow in the wall region of a larger-diameter riser compared to a smaller-diameter riser.

### Conclusions

By examining the effects of gas velocity, solids circulation rate, loading ratio and properties of coarse particles as well as the bed diameter on the apparent and fine solids holdup profiles of the binary solids circulating fluidized beds, it was found that with the addition of coarse particles the apparent and fine solids holdups are both varied. The variation is dependent on the equilibrium between the effect of increase in fine particles velocity caused by an increase of interstitial gas velocity resulting from a decrease of the effective cross area of flow and the effect of the interaction between fine and coarse particles. With an increase in gas velocity, the profile of fraction of coarse particles along the bed height becomes more uniform, resulting from the full entrainment and circulation of coarse particles, and thus the effect of the loading ratio of the coarse particles becomes negligible.

### Nomenclature

- $D$ = bed diameter [m]
- $d_p$ = particle diameter [m]
- $G_s$ = solids circulation rate [kg/(m²s)]
- $H$ = riser height [m]
- $P$ = pressure [Pa]
- $U_g$ = superficial gas velocity [m/s]
\[ U_t = \text{terminal velocity of a single particle} \quad [\text{m/s}] \]
\[ x_c = \text{cross-sectionally averaged fraction of coarse particles in a certain axial position} \quad [-] \]
\[ x_{00} = \text{fraction of coarse particles loaded (at the beginning of the operation)} \quad [-] \]
\[ x_{c, \text{ave}} = \text{averaged fraction of coarse particles over the bed height (see Eq. (3))} \quad [-] \]
\[ z = \text{bed axial coordinate} \quad [\text{m}] \]
\[ \varepsilon = \text{cross-sectional averaged voidage} \quad [-] \]
\[ \rho_{pc} = \text{density of coarse particles} \quad [\text{kg/m}^3] \]
\[ \rho_{df} = \text{density of fine particles} \quad [\text{kg/m}^3] \]

**Literature Cited**