Effect of Surface Morphology on the Flow of Entrained Fine Particles by Ascending Gas through Packed Beds

Nobuyuki Hidaka*, Toshitatsu Matsumoto, Katsuki Kusakabe* and Shigebaru Morooka*

Department of Applied Chemistry and Chemical Engineering, Kagoshima University, Kagoshima 890-0065, Japan
*Department of Material Physics and Chemistry, Graduate School of Engineering, Kyushu University, Fukuoka 812-8581, Japan
(Received 20 May 1999 • accepted 6 September 1999)

Abstract—Coarse particles of glass or cokes were packed in vertical columns, 1- and 2-m in height, and fine particles of glass or coke were entrained through the columns by the ascending gas flow. These systems were used as a model to investigate the flow of fine coal particles introduced into a blast furnace. The effects of properties of packed particles, as well as fines, on the static and dynamic holdups of fines were then investigated. The static holdup of fines was strongly affected by the surface roughness of the packed particles, while the dynamic holdup of fines was not. These results suggest that the fine particles are trapped in the form of static holdup in the isolated narrow spaces bounded with packed particles, and that they remain on the surface of the packed particles which are exposed to the gas flow for only a short period of time.

Key words: Entrainment, Blast Furnace, Packed Bed, Gas-Solid Flow, Holdup

INTRODUCTION

Coal particles are injected into the raceway of a blast furnace through tuyeres. When the injection rate of coal particles into the furnace is increased, a large number fines are generated, which accumulate unevenly, resulting in an unexpected distribution of gas flow in the bed [Yamaoka, 1986a, b; Shibata et al., 1991; Kusakabe et al., 1991a, b; Aoki et al., 1993; Yagi, 1993; Chen et al., 1994; Ariyama et al., 1996; Sugiyama, 1996]. A portion of the fines is entrained by the ascending gas, while the remainder is trapped in the stagnant spaces of the packed bed. The volume fraction of the former particles per unit volume of the bed is referred to as “dynamic holdup,” and that of the latter as “static holdup.” Kusakabe et al. [1991a, b] directly measured the ascending velocity of fine particles using a pair of optical fiber probes. Hidaka et al. [1998, 1999] investigated the dynamic and static holdups of fines over a wide range of operating conditions in 1- and 2-m high packed beds and correlated these holdups with empirical equations. The surface morphology of coarse particles which were packed in the bed, as well as that of fines which were introduced into the bed, had a strong influence on the flow of the fines. At the present time, however, the effect of the surface morphology on the holdup of fines is not well understood, although it is an important issue in terms of estimating complicated flow which occurs in blast furnaces [Yagi, 1993]. The present study describes experiments wherein sieved glass beads, or coke particles, were used as fines and were upwardly entrained in vertical beds packed with coarse glass spheres or pulverized coke particles.

†To whom correspondence should be addressed.
E-mail: hidaka@cen.kagoshima-u.ac.jp

EXPERIMENTAL

Fig. 1 shows a schematic diagram of the experimental apparatus used in the packed bed experiments. Two vertical columns (93.5 mm i.d. and 1.03 m in height; 93.5 mm i.d. and 2.03 m in height) were constructed of acrylic resin tubes. Both the bottoms and tops of the beds were conical in shape, for ease in distributing and collecting the gas-solid mixed flow, respec-

†To whom correspondence should be addressed.
E-mail: hidaka@cen.kagoshima-u.ac.jp

1. Blower
2. Heat exchanger
3. Orifice meter
4. Hopper
5. Screw feeder
6. Pressure tap
7. Packed bed
8. Cyclone
9. Switching valve
10. Collector

Fig. 1. Schematic diagram of experimental apparatus.
Effect of Surface Morphology on the Flow of Entrained Fine Particles by Ascending Gas through Packed Beds

Table 1. Properties of the packing particles used

<table>
<thead>
<tr>
<th>Material</th>
<th>Diameter [mm]</th>
<th>Voidage (1 - \varepsilon_p)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass sphere (CGS)</td>
<td>4.65</td>
<td>0.35</td>
</tr>
<tr>
<td>Pulverized coals (CPC)</td>
<td>2.37*</td>
<td>0.50</td>
</tr>
<tr>
<td></td>
<td>2.85*</td>
<td>0.51</td>
</tr>
</tbody>
</table>
*a*equivalent diameter calculated from Ergun’s equation

Table 2. Properties of the fines used

<table>
<thead>
<tr>
<th>Material</th>
<th>Diameter [μm]</th>
<th>Density [kg m(^{-3})]</th>
<th>Terminal velocity*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass beads (FGB)</td>
<td>65</td>
<td>2500</td>
<td>0.28</td>
</tr>
<tr>
<td></td>
<td>118</td>
<td>2500</td>
<td>0.76</td>
</tr>
<tr>
<td>Pulverized coke (FPC)</td>
<td>125</td>
<td>1900</td>
<td>0.65</td>
</tr>
</tbody>
</table>
*a*calculated values

Fig. 2. Effect of the feed rate of fines and the packed bed height on static holdup. The solid lines in (A)-(C) are calculated from Eq. (2), and the lines in (D)-(F) are calculated from Eq. (3).

FPC-CGS system, \(d_f = 4.65\) mm, \(d_t = 125\) μm, (A) \(G_1 = 0.1\) kg m\(^{-3}\) s\(^{-1}\), (B) \(G_2 = 0.3\) kg m\(^{-3}\) s\(^{-1}\), (C) \(G_3 = 0.6\) kg m\(^{-3}\) s\(^{-1}\); FPC-CPC system, \(d_f = 2.85\) mm, \(d_t = 125\) μm, (A) \(G_1 = 0.1\) kg m\(^{-3}\) s\(^{-1}\), (B) \(G_2 = 0.3\) kg m\(^{-3}\) s\(^{-1}\), (C) \(G_3 = 0.6\) kg m\(^{-3}\) s\(^{-1}\); packed bed height, \(\Theta 1.03\) m, \(\triangle 2.03\) m.

 exploits. Fine particles were fed from a hopper using a screw feeder and were injected into the feed gas stream. The gas-solid mixture was then introduced into the packed bed through a single 13-mm i.d. nozzle, which was located at the center of the cone. To prevent the fall of coarse particles from the bottom of the bed, a 9 mesh stainless steel net was attached to the top of the nozzle. Fines, which were entrained in the effluent gas, were recovered with a cyclone covered filter net on the gas outlet. In order to measure pressure difference, pressure taps were installed on the column wall.

Ambient air was used as the gas phase, and the bed was packed with glass spheres (CGS) with an average diameter of 4.65 mm and pulverized coke (CPC) with average diameters of 2.37 and 2.85 mm. The fines were sieved glass beads (FGB), 65 and 118 μm in diameter, and sieved coke particles (FPC), 125 μm in diameter. The properties of these particles are listed in Table 1 and 2. Hereafter, an “A-B system” indicates that fines A ascend through a bed packed with particles B. The feed rate of the fines per unit area of the bed is calculated from the mass of fines collected by the cyclone.

A steady state was attained in the bed, after the gas and fines had been continuously fed for 10-20 min. The feed of fines was then stopped, and the collection of fines was initiated at the exit by diverting the solid flow to a reservoir. Dynamic holdup was determined from the mass of the collected fines divided by the volume of the bed. The superficial gas velocity was then increased to above 1.5 m s\(^{-1}\), and the fines which remained trapped among the packings were stripped and collected at the exit. Static holdup was determined from the mass of the stripped fines divided by the volume of the bed. The completeness of stripping was confirmed by observation through the transparent bed wall.

RESULTS AND DISCUSSION

1. Pressure Drop and Static Holdup of Fines in Packed Beds

The pressure drop through the bed, packed with CGS particles, was in agreement with Ergun’s equation as shown in our previous paper [Hidaka et al., 1999].

\[
\Delta P = \frac{150\eta U_e \varepsilon_p}{d_f^3 (1-\varepsilon_p)^3} + \frac{1.75\rho U_e^{2.5} \varepsilon_p}{d_f (1-\varepsilon_p)^3} \tag{1}
\]

The size of the CPC particles was determined as shown in Table 1, assuming that the pressure drop with no feed fines agreed with Eq. (1). The voidages in the packed beds are also listed in Table 1.

Fig. 2 shows the experimental data for static holdup for the FPC-CGS (A-C) and FPC-CPC systems (D-F) for the cases of the 1- and 2-m high packed beds, respectively. The static holdup decreased with increasing superficial gas velocity, and was virtually the same for both the 1- and 2-m high packed beds. No effect of the feed rate of fines on the static holdup was observed. However, the surface roughness of the coarse particles rather than the shape of the fine particles had a strong impact on the static holdup.

Hidaka et al. [1998, 1999] correlated static holdup data with the following empirical equations.

For the case of the FGB-CGS system,

\[
H_e/\rho = c_1(U_e)^{1.0} + c_2(U_e)^{0.5} d_f^{1.0}/\rho \tag{2}
\]

and for the case of the FGB-CPC system,

\[
H_e/\rho = c_1U_e^{1.2} \tag{3}
\]

where \(c_1 = 1.1 \times 10^4\), \(c_2 = 1.8 \times 10^2\), \(c_3 = 5.7 \times 10^3\). The quantities in Eqs. (2) and (3) must be expressed in the base SI units. The static holdup is divided by the density of fines, since it is the volume of the fines that is meaningful, rather than their mass.