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

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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.

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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-

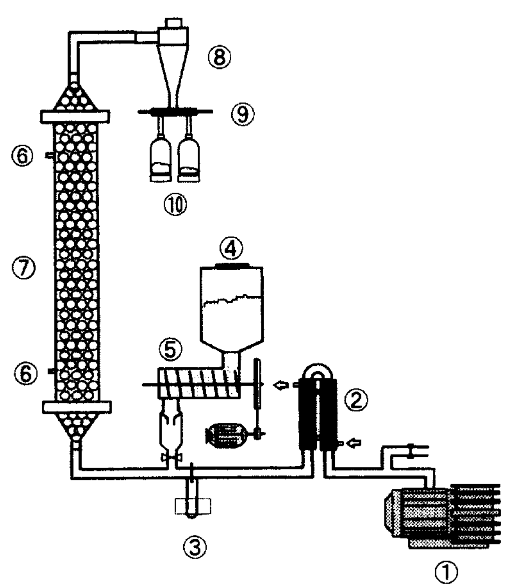

Fig. 1. Schematic diagram of experimental apparatus.

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

Table 1. Properties of the packing particles used

Material	Diameter [mm]	Voidage $(1-\varepsilon_p)$
Glass sphere (CGS)	4.65	0.35
Pulverized cokes (CPC)	2.37*	0.50
	2.85*	0.51

*equivalent diameter calculated from Ergun's equation

Table 2. Properties of the fines used

Material	Diameter [μm]	Density [kg·m^{-3}]	Terminal velocity* [m·s^{-1}]
Glass beads (FGB)	65	2500	0.28
	118	2500	0.76
Pulverized coke (FPC)	125	1900	0.65

*calculated values

tively. 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 beds, packed with CGS particles, was in agreement with Ergun's equation as shown in our previous paper [Hidaka et al., 1999].

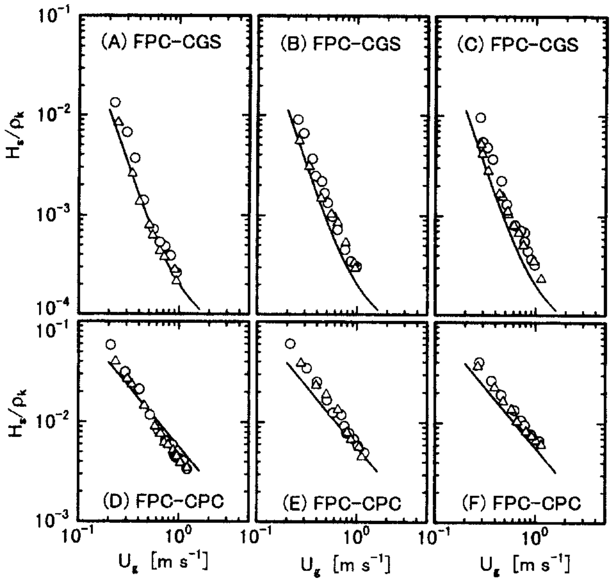

Fig. 2. Effect of the feed rate of fines and the packed bed height on static holdup. The solid lines in (A)-(C) are calculated from Eq. (2), and the lines in (D)-(F) are calculated from Eq. (3).
FPC-CGS system, d_p=4.65 mm, d_k=125 μm, (A) G_k=0.1 kgm^{-2}s^{-1}, (B) G_k=0.3 kgm^{-2}s^{-1}, (C) G_k=0.6 kgm^{-2}s^{-1}; FPC-CPC system, d_p=2.85 mm, d_k=125 μm, (A) G_k=0.1 kgm^{-2}s^{-1}, (B) G_k=0.3 kgm^{-2}s^{-1}, (C) G_k=0.6 kgm^{-2}s^{-1}; packed bed height, ○ 1.03 m, △ 2.03 m.

$$\frac{\Delta P}{L}=\frac{150\eta U_g}{d_p^2}\frac{\varepsilon_p^2}{(1-\varepsilon_p)^3}+\frac{1.75\rho_g U_g^2}{d_p}\frac{\varepsilon_p}{(1-\varepsilon_p)^3} \tag{1}$$

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,

$$H_s/\rho_k=c_1[U_g^{-3.0}+c_2U_g^{-0.5}d_p^{-1.0}]/\rho_g^{3.0} \tag{2}$$

and for the case of the FGB-CPC system,

$$H_s/\rho_k=c_3U_g^{-1.2} \tag{3}$$

where c_1=1.1×10^{-4}, c_2=1.8×10^{-2}, c_3=5.7×10^{-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.

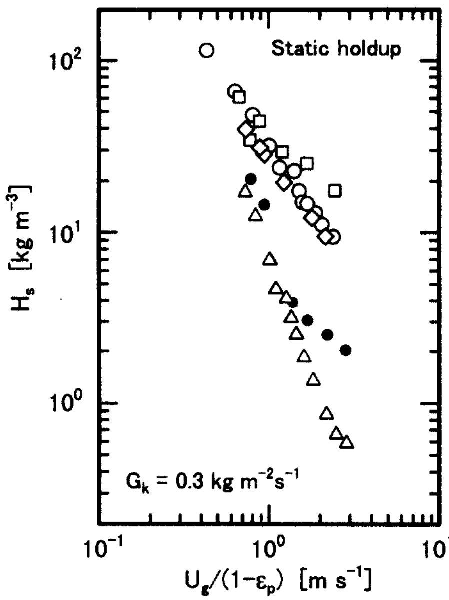

Fig. 3. Effects of the surface morphology of packed particles and the shape of fines on static holdup.
FPC-CPC system, ○, d_p=2.85 mm, d_k=125 μm; FPC-CGS system, △, d_p=4.65 mm, d_k=125 μm; FGB-CGS system, ●, d_p=4.65 mm, d_k=118 μm; FGB-CPC system, □, d_p= 2.37 mm, d_k=65 mm; FGB-CPC system, ◇, d_p=2.37 mm, d_k=118 μm.

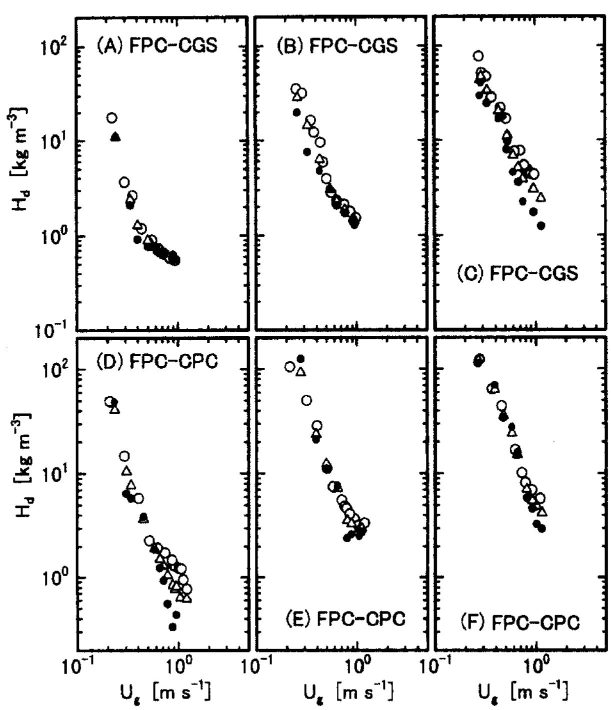

Fig. 4. Effect of the feed rate of fines and the packed bed height on dynamic holdup.
FPC-CGS system, d_p=4.65 mm, d_k=125 μm [kgm^{-2}s^{-1}]; (A) G_k=0.1 km^{-2}s^{-1}, (B) G_k=0.3 kgm^{-2}s^{-1}, (C) G_k=0.6 kgm^{-2}s^{-1}; FPC-CPC system, d_p=2.85 mm, d_k=125 μm, (A) G_k=0.1 kgm^{-2}s^{-1}, (B) G_k=0.3 kgm^{-2}s^{-1}, (C) G_k=0.6 kgm^{-2}s^{-1}; bed height, ○ 1.03, △ 2.03, ● in the upper 1-m portion of the 2-m high packed bed.

The solid lines in Fig. 2 represent values calculated from Eqs. (2) and (3), suggesting that these equations are applicable to the experimental data for the cases of the FPC-CGS and the FPC-CPC systems.

Fig. 3 shows the effects of the combinations of packed particles and fines on the static holdup of fines. In order to express these data in a form which can be compared with the dynamic holdup described in the next section, the static holdup is expressed in units of mass. The values in the CPC-packed bed are much larger than those for the case of the CGS-packed bed. Thus, the static holdup is strongly dependent on the morphology of the packed particles, and the surface morphology of the fines used in the present study does not appear to be a dominant factor.

2. Dynamic Holdup of Fines in Packed Beds

Fig. 4 shows the experimental data relative to the dynamic holdup for the FPC-CGS (A-C) and FPC-CPC systems (D-F) as functions of the height of packed beds and the feed rate of fines. The dynamic holdup sharply decreased with increasing gas velocity in the range of U_g<0.5-0.8 m·s^{-1} and, thereafter, gradually decreased with increasing gas velocity. The same trends were found for static holdup. Hidaka et al. [1998, 1999] found that the dynamic holdup data for the 1-m high packed beds were larger than those for the 2-m high packed beds when the 65-μm diameter FGB was used as fines. For the other systems, no significant differences in dynamic holdup for the 1- and 2-m high packed beds were observed, as shown in Fig. 4.

In contrast to static holdup, the dynamic holdup was increased with increasing feed rate of fines, but was not affected by the surface roughness of the coarse particles. This trend is

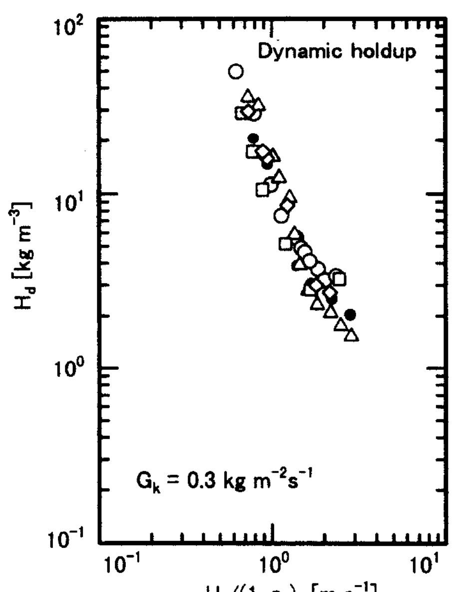

Fig. 5. Effects of the surface roughness of packed particles and the shape of fines on dynamic holdup.
FPC-CPC system, ○, d_p=2.85 mm, d_k=125 μm; FPC-CGS system, △, d_p=4.65 mm, d_k=125 μm; FGB-CGS system, ●, d_p=4.65 mm, d_k=118 μm; FGB-CPC system, □, d_p=2.37 mm, d_k=65 μm; FGB-CPC system, ◇, d_p=2.37 mm, d_k= 118 μm.

clearly shown in Fig. 5. Hidaka et al. [1999] reported that the dynamic holdup was not affected by the diameter of fines. These differences between the static and dynamic holdups can be explained as follows:

(1) The fines, which are retained as the static holdup, are trapped in the isolated narrow spaces between packed particles. Particles with rougher surfaces are capable of holding up larger amounts of fines.

(2) The fines, which are recovered as the dynamic holdup, are continuously entrained by the ascending gas flow. Hidaka et al. [1998, 1999] have proposed a model for the movement of a fine particle which undergoes repeated collision with the surface of a packed particle, assuming that the velocity of the fine particle in the vertical direction becomes zero at the moment of the collision and thereafter increases to a steady state value. However, the values of the dynamic holdup estimated based on this model are lower than the experimental values for the smaller and lighter fines, and are higher for the coarser and heavier fines. This suggests that the fine particles are not stopped on the surface of the packed particles at the time of collision for an extended period.

CONCLUSIONS

A mixture of gas and fines was injected into the bottom of packed beds, and the dynamic and static holdups of fines were determined as functions of the rate of gas flow and the properties of fines and packing particles. The static holdup was dependent on the roughness of the surface of the packed particles, while the dynamic holdup was not. The surface roughness of the fines was not a dominant factor for the case of either static or dynamic holdup.

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NOMENCLATURE

d_k : diameter of fines [m]
d_p : diameter of packed particles [m]
G_k : feed rate of fines [$kgm^{-2}s^{-1}$]
g : gravitational acceleration [ms^{-2}]
H : bed height [m]
H_d : dynamic holdup of fines [kgm^{-3}]
H_s : static holdup of fines [kgm^{-3}]
L : distance between pressure taps [m]
ΔP : pressure drop in bed [Pa]
U_g : superficial gas velocity [ms^{-1}]
ε_p : volumetric fraction of packing particles in packed bed [-]
η : viscosity of gas [Pa·s]
ρ_g : density of gas [kgm^{-3}]
ρ_k : density of fine particles [kgm^{-3}]

REFERENCES

Aoki, R., Nogami, H., Tsuge, H., Miura, T. and Furukawa, T., "Simulation of Transport Phenomena around the Raceway Zone in the Blast Furnace with and without Pulverized Coal Injection," *ISIJ Intern.*, **33**, 646 (1993).

Ariyama, T., Sato, M. and Asakawa, Y., "Mean Ascending Velocity of Powder Entrained by Gas in a Packed Bed," *Kagaku Kogaku Ronbunshu*, **22**, 171 (1996).

Chen, J., Nogami, H., Akiyama, T., Takahashi, R. and Yagi, J., "Behavior of Powders in a Packed Bed with Lateral Inlets," *ISIJ Intern.*, **34**, 133 (1994).

Hidaka, N., Iyama, J., Matsumoto, T., Kusakabe, K. and Morooka, S., "Entrainment of Fine Particles with Upward Gas Flow in a Packed Bed of Coarse Particles," *Powder Technol.*, **95**, 285 (1998).

Hidaka, N., Matsumoto, T., Kusakabe, K. and Morooka, S., "Flow of Fine Particles Entrained by Upward Gas Flow in Packed Beds of Coarse Particles," *J. Chem. Eng. Japan*, **32**, 197 (1999).

Kusakabe, K., Yamaki, T., Morooka, S. and Matsuyama, H., " Percolating Velocity of Fine Particles through Packed Bed of Coarse Particles," *Tetsu-to-Hagane*, **77**, 1407 (1991a).

Kusakabe, K., Yamaki, T. and Morooka, S., "Direct Measurement of Ascending Flow of Fines through Packed Bed of Coarse Particles," *Tetsu-to-Hagane*, **77**, 1413 (1991b).

Shibata, K., Shimizu, M., Inaba, S., Takahashi, R. and Yagi, J., "Pressure Loss and Hold-up Powders for Gas-Powder Two Phase Flow in Packed Beds," *ISIJ Intern.*, **31**, 434 (1991).

Sugiyama, T., "Experimental and Numerical Analysis on the Movement and Accumulation of Powder in the Deadman and the Dripping Zone of Blast Furnace," *Tetsu-to-Hagane*, **82**, 29 (1996).

Yagi, J., "Mathematical Modeling of the Flow of Four Fluids in a Packed Bed," *ISIJ Intern.*, **33**, 619 (1993).

Yamaoka, H., "Flow Characteristics of Gas and Fine Particles in Packed Bed," *Tetsu-to-Hagane*, **77**, 403 (1986a).

Yamaoka, H., "Flow Characteristics of Gas and Fine Particles in a Two-Dimensional Space of Packed Bed," *Tetsu-to-Hagane*, **77**, 2194 (1986b).