SEGREGATION OF PARTICLES IN BINARY SOLIDS CIRCULATING FLUIDIZED BEDS

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The segregation pattern of particles in circulating fluidized beds, 0.097 m and 0.150 m in diameter and 3 m in height, was investigated by using two groups binary solid particles that are different in diameter and density. The influence of operating conditions on the extent of particle segregation were examined. An empirical correlation for describing the extent of segregation was proposed. For distinguishing the segregation/mixing flow pattern, a theoretical criterion was derived and a segregation diagram was then prepared.

Introduction

As industrial practice and development of circulating fluidized bed (CFB) technology advance, the knowledge of solids mixing and segregation in the reactors is growing in importance[5, 6]. This is mainly due to the following reasons. Firstly, in some processes the solids treated are generally have a wide size distribution depending on the material sources such as coal and waste combustion in the CFB. Secondly, it is known that effective gas-solids contact and a uniform flow structure can be achieved in a bed with multi-component or mixed-size particles[2]. Finally, processes in which the solids sizes are progressively varied are frequently encountered. It is well known that when particles differing in size and/or density are fluidized in a bed, the segregation occurs, i.e. most of the heaviest/largest particles descend to the bottom while most of the lightest/smallest ones remain in the upper region, depending on the difference in particle sizes and densities and on operating conditions. While a considerable amount of research has been carried out on hydrodynamics in CFBs, where the solids size distributions are generally narrow and thus the solids can be treated as a single-size solid, operation of CFBs with multi-component solids has been reported in only a few studies[1, 3, 4, 7, 8]. Especially, information about axial particle segregation in the multi-solids CFB is still insufficient for proper design and operation.

In this work the mixing and segregation pattern in circulating fluidized beds consisting of density- and size-different particles were investigated. Particular attention has been focused on understanding the interaction mechanism between the particles and the conditions in which complete mixing or segregation should be observed in the CFBs.

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1. Experimental

A schematic diagram of the circulating fluidized bed used in this study is shown in **Fig. 1**. Two risers, made of acrylic pipes, 0.097 m and 0.15 m in diameter and 3 m in height, were used. Air from a roots-type blower was introduced to the riser through a distributor, and the flow rate was controlled by a standard orifice meter to achieve the desired superficial gas velocity. The flow of solids from the reservoir into the base of the riser was controlled with the aid of a loopseal pneumatic valve by regulating the horizontal and vertical aeration to the valve. Entrained particles were separated from air at the exit of the riser by a two-stage cyclone system and then returned to the solids reservoir, in which the solids inventory was carefully controlled at a level of 1.7 m height with the aid of the solids hopper. A diversion valve was installed below the primary cyclone to measure the solids circulation rate by diversion of the solids leaving the primary cyclone (> 99 % efficient) into a measuring tank. Diverted solids could be reloaded into the system with the aid of a solids hopper located at the top of the reservoir while the apparatus was in operation. Before the experiments, the volume ratio of coarse particles to mixed particles, x_{c0}, was fixed at a desired value in the solids hopper. The axial pressure profile along the riser was measured by a pressure sensor which could be connected to pressure taps installed along the riser wall.

Segregation patterns were described by the axial profiles of the volumetric fraction of coarse particles, x_c. This was done by drowing a small quantity of bed mate-

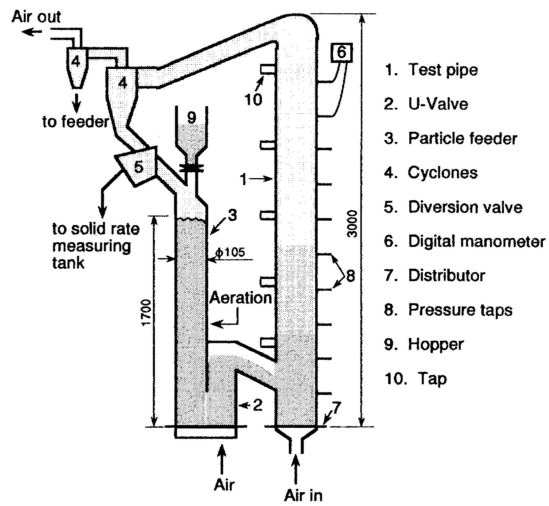


Fig. 1 Schematic diagram of the experimental apparatus

Table 1. Properties of particles used in the present experiments

Items	d_p [μm]	ρ_p [kg/m^3]	U_t [m/s]	Geldart's group
FCC	69.7	1702	0.249	A
Silica sand	321	2644	2.63	B
Activated alumina	633	1271	3.18	B

rial quickly through one of six sampling tubes installed at six different positions along the riser. The composition of each sample, i.e., the volumetric fraction of coarse particles, x_c, was determined by weighing the individual components after sieving.

In all the experiments, FCC catalysts were used as the fine particles while silica sand and activated alumina were used separately as coarse particles. Properties of both the fine and coarse particles are listed in **Table 1**.

2. Results and Discussion

2.1 Axial segregation pattern

Typical axial profiles of coarse particle fraction, x_c, are shown in **Fig. 2** . From Fig. 2 (a), it is found that at a low gas velocity, rather smaller than the terminal velocity of a single coarse particle and at a solids circulation rate that is also low [G_s = 7.39 kg/(m^{2}s)], x_c is quite large in the bottom section and close to zero at the riser-exit. This may be attributed to the low drag force acted by the gas and fine particle stream which is too small to transport the coarse particles out of the riser. We termed this state *complete segregation*. When the solids circulation rate is increased [G_s = 11.5 kg/(m^{2}s)], due to the enhancement in drag force acting on the coarse particles from the gas and fine particle stream, the coarse particles start to be partially entrained by the gas and fine particles stream and eventually are carried out of the riser. As a result, a typical *segregation* pattern of particles, characterized by a nonuniform axial profile of x_c consisting of a high value in the bottom section and a low one in the

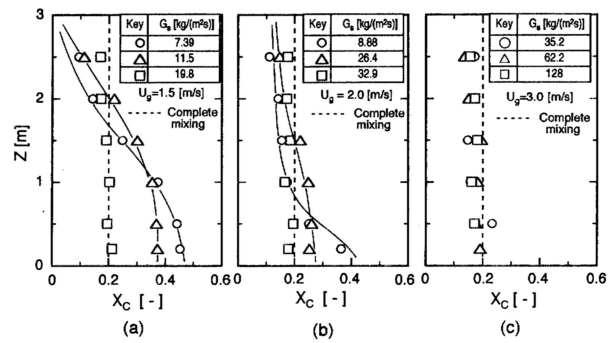


Fig. 2 Axial segregation pattern of particles (Solids: Silica sand/FCC, D = 0.097 m)

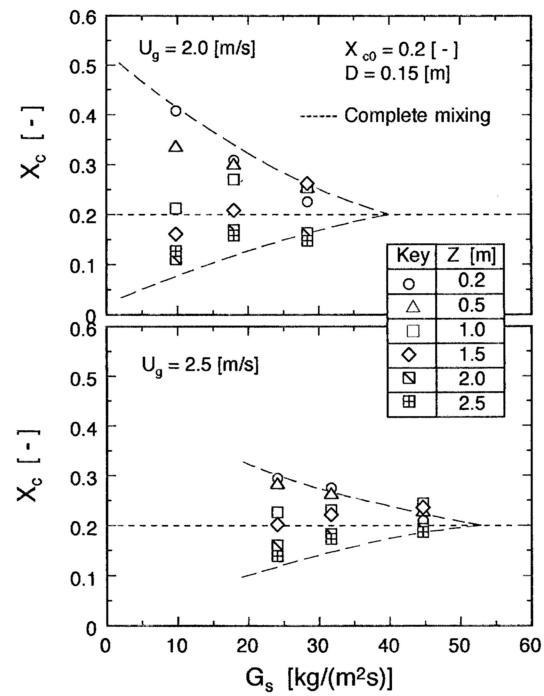


Fig. 3 Effect of Gs on axial segregation of particles (Solids: Silica sand/FCC, D = 0.097 m)

upper section, is observed. As the solids circulation rate is further increased [G_s = 19.8 kg/(m^{2}s)], the drag force due to gas and the fine particles stream can become so large that the coarse particles can be fully circulated and a uniform axial distribution of x_c is then obtained. This means that a *complete mixing* state in the riser has been achieved.

When the gas velocity is increased to approach the terminal velocity of a single coarse particle, as shown in Fig. 2 (b), (U_g = 2.0 m/s), the coarse particles can be entrained and circulated especially due to the enhancement of gas drag even at a low solids circulation rate. On comparing Figs. 2 (a) and (b), it is seen that the segregation of particles becomes weak when gas velocity is increased.

At a high gas velocity, larger than the terminal velocity of a single coarse particle (Fig. 2 (c), U_g = 3.0 m/s), a much more uniform axial distribution of x_c is observed in the range of solids circulation rate used in

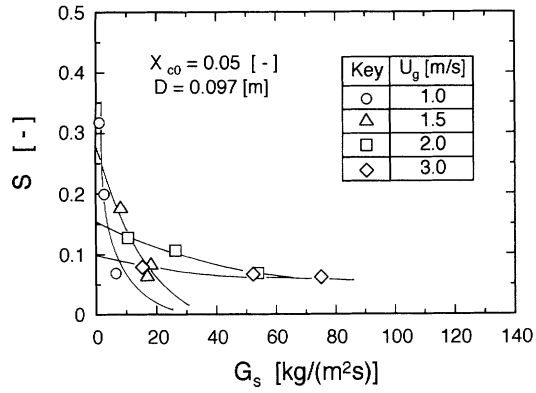


Fig. 4 Effect of gas velocity on the extent of particle segregation (Solids: Silica sand/FCC, $x_{c0} = 0.2$, $D =$ 0.097 m)

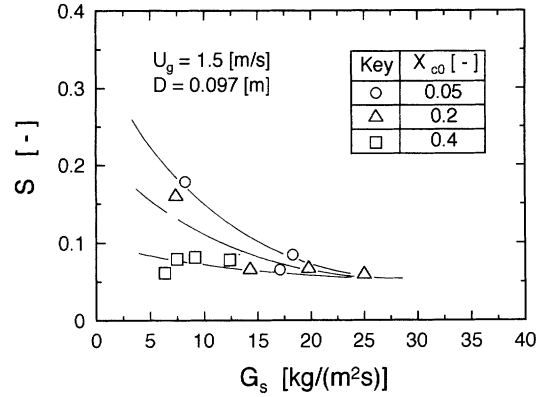


Fig. 5 Effect of the loading ratio on the extent of particle segregation.(Solids: Silica sand/FCC, $U_g = 1.5$ m/s, $D =$ 0.097 m)

this study. This is due to the significant drag force on the coarse particles acted upon by the gas and the fine solids stream in such conditions. The result that x_c at different axial positions closes to x_{c0} indicates that a complete mixing state was present in the riser.

The axial segregation of particles can also be illustrated by plotting x_c obtained at various axial positions against solids circulation rate, as shown in **Fig. 3**. As seen from the Figure, two adverse changes of x_c, i.e., decrease in lower sections and increase in upper sections, are clearly revealed when the solids circulation rate is increased. Consequently, the difference in x_c between the bottom and top of the bed is large but decreases with increasing G_s, and finally approaches zero when G_s attains a certain value.

2.2 Extent of particle segregation and influencing factors

To measure the extent of particle segregation quantitatively, segregation intensity, S, is defined as follows.

$$S = \frac{1}{H}\int_0^H \left(\frac{x_c - x_{c,ave}}{x_{c,ave}}\right)^2 dz \tag{1}$$

where

$$x_{c,ave} = \frac{1}{H(1-\varepsilon_{ave})}\int_0^H (1-\varepsilon)\, x_c\, dz \tag{2}$$

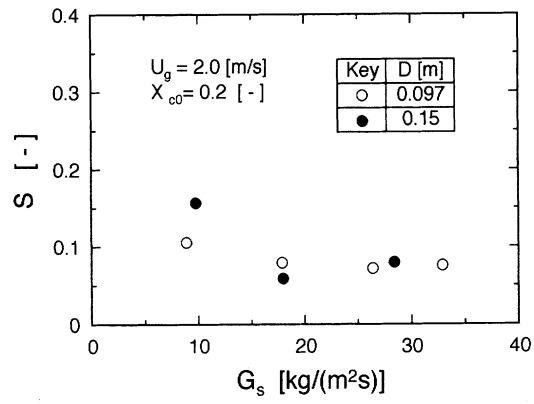


Fig. 6 Effect of the bed diameter on the extent of particle segregation.(Solids: Silica sand/FCC, $U_g = 2.0$ m/s, $x_{c0} = 0.2$)

It is clear that the larger the value of S, the stronger is the segregation of particles, and vice versa.

Figure 4 shows the variation of S with solids circulation rate at various gas velocities. It is indicated again that the extent of particle segregation decreases with increasing solids circulation rate at a given x_{c0}. **Figure 5** is interesting to note in that the extent of particle segregation becomes smaller when x_{c0} is increases at a given gas velocity and solids circulation rate. This is plausible because as x_{c0} increases, the drag force between gas and coarse particles increases. This is due to the increase of interstitial gas velocity resulting from the decrease of effective cross-sectional area of flow. The increase in drag force makes the coarse particles transport upwards more easily. However, Fig. 5 also shows that when the bed is operated at a higher solids circulation rate, the effect of x_{c0} on the extent of particle segregation will become negligible.

On comparing the results obtained in the riser of 97 mm diameter with those of the 150 mm diameter riser, as plotted in **Fig. 6**, it is seen that under the same operating conditions the effect of bed diameter on the extent of particle segregation is negligible.

In summary, the extent of particle segregation is influenced by many factors, as described above. According to the experimental observations, the following correlation for S is considered.

$$S = a\ \exp\left(-b\left(\frac{G_s}{\rho_{pc}\, x_{c0}\, U_{tc}}\right)\right) \tag{3}$$

As seen from **Fig. 7**, a and b varied considerably with U_g, x_{c0} and solids properties. By using the linear regression method the following formulas for a and b are found.:

$$a = 0.115\left(\frac{U_{tc}-U_{tf}}{U_g-U_{tf}}\right)^{1.69} x_{c0}^{-0.18}\left(\frac{\rho_{pc}}{\rho_{pf}}\right)^{0.97} \tag{4}$$

$$b = 189.4\left(\frac{U_{tc}-U_{tf}}{U_g-U_{tf}}\right)^{2.01} x_{c0}^{1.06}\left(\frac{\rho_{pc}}{\rho_{pf}}\right)^{1.74} \tag{5}$$

with standard errors of estimation $\sigma^2 = 0.381$ and 0.262, respectively. Figure 7 also shows that S calculated from

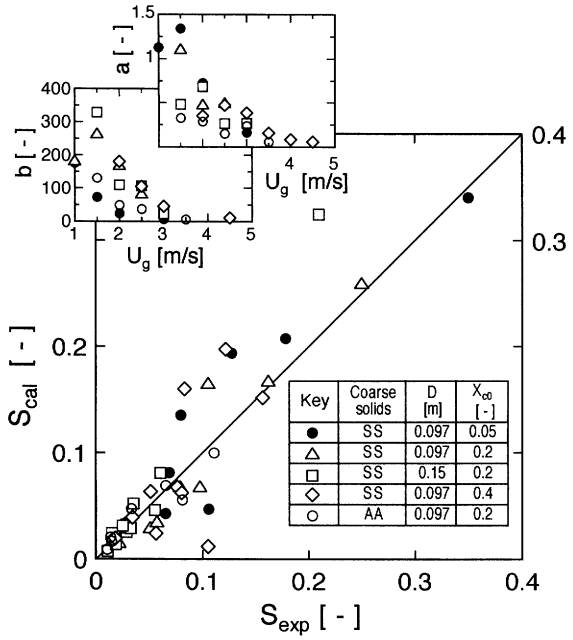


Fig. 7 Comparison of calculated S with experimentally determined S for various conditions showing the variations in a and b

Eqs. (3) to (5) can describe the experimentally determined S within 30% average deviation.

2.3 Prediction of the segregation-mixing flow pattern

Extensive efforts have been made in analyzing the experimental observations. As mentioned earlier, when the coarse particles are fully entrained the segregation of particles disappears in a binary CFB. In that case it is therefore reasonable to assume that the slip velocity of coarse particles at the exit of the bed should satisfy the following relationship.

$$U_{slc} = \frac{U_g}{\varepsilon_{exit}} - V_c \geq U_{tc} \tag{6}$$

For any section of the bed, the solids mass balance can be expressed as

$$G_s = \rho_{pc} x_c (1-\varepsilon) V_c + \rho_{pf} (1-x_c)(1-\varepsilon) V_f \tag{7}$$

Noting that at the state of complete mixing x_c at any height of the bed becomes equal to x_{co}, and making an assumption of

$$V_f = \frac{U_g}{\varepsilon_{exit}} - U_{tf} \tag{8}$$

for fine particles at the exit of the bed, which is reasonable because the effect of cluster formation can be ignored due to the extremely low solids concentration at the bed exit, we can obtain the following equation by combining Eqs. (6) to (8).

$$\frac{U_g}{\varepsilon_{exit}} \geq \frac{U_{tc} + \dfrac{\rho_{pf}(1-x_{c0})}{\rho_{pc} x_{c0}} U_{tf} + \dfrac{G_s}{\rho_{pc} x_{c0} (1-\varepsilon_{exit})}}{1 + \dfrac{\rho_{pf}(1-x_{c0})}{\rho_{pc} x_{c0}}}$$

$$= \frac{U_g^*}{\varepsilon_{exit}} \text{ for mixing state} \tag{9}$$

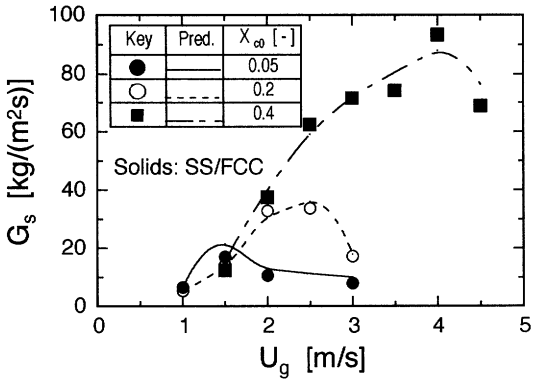


Fig. 8 Diagram for describing segregation (the region below the lines) and mixing flow states in binary CFBs

For a given operating condition, the flow patterns, i.e., segregation or mixing, can be determined by Eq. (9) if the voidage at the bed exit has been experimentally measured. For the system of silica sand/FCC, the transition gas velocities obtained from Eq. (9) by replacing the voidage ε_{exit} by the measured voidage at the exit of bed are plotted against the solids circulation rates for three x_{c0} values in **Fig. 8**. As shown in the Figure, good agreement between the prediction and experiments is clearly obtained. It is interesting to note that at a given x_{c0}, with increasing U_g the value of G_s for transition from segregation to mixing state increases initially, reaches a maximum value, and finally falls rapidly when the gas velocity has excceded the terminal velocity of coarse particles in the two-phase flow. From this Figure it is also seen that when x_{c0} is increased the operating gas velocities and solids circulation rates for the segregation state will become wider.

Conclusions

1. The segregation pattern of particles has been observed in CFBs with binary solid particles that are different in diameter and density. The extent of particle segregation has been recognized by examining the influencing factors such as gas velocity, solids circulation rate and particle properties as well as bed diameter.

2. An empirical correlation for estimating S is proposed.

3. A theoretical equation and a diagram for describing the segregation-mixing flow pattern in a binary CFB are proposed.

All experiments presented here show that the behavior of a binary CFB is significantly dependent on the interaction between fine and coarse particles. A further theoretical modeling is currently being carried out.

Nomenclature

D	=	bed diameter	[m]
d_p	=	particle diameter	[m]
G_s	=	solids circulation rate	[kg/(m²s)]
P	=	pressure	[Pa]
S	=	index of particle segregation defined by Eq. (1)	[-]

U, V	=	velocities of gas and particles, respectively	[m/s]
U_g^*	=	the transition gas velocity between the segregation and mixing states	[m/s]
U_{sl}	=	slip velocity	[m/s]
U_t	=	terminal velocity of a single particle	[m/s]
x	=	the ratio of coarse particles to mixed particles in volume	[-]
z	=	bed axial coordinate	[m]
ε	=	the cross-sectional averaged voidage	[-]
ρ_p	=	density	[kg/m^3]
σ^2	=	variance	[-]

<Subscripts>

0	=	loading (at beginning of operation)
ave	=	averaged over whole bed height
c	=	coarse particles
exit	=	at riser exit
f	=	fine particles
g	=	gas

Literature Cited

1) Arastoopour, H., C.-H. Wang and S.A. Weil: *Chem. Eng. Sci.*, **37**, 1379-1386 (1982)
2) Bi, H.-T., P.-J. Jiang, R.-J. Jean and L.-S. Fan: *Chem. Eng. Sci.*, **47**, 3113-3124 (1992)
3) Horio, M., K. Morishita and O. Tachibana: *World Congress III of Chem. Eng.*, p. 536-539, Tokyo, Japan (1986)
4) Ijichi, K., Y. Tanada, K. Yoshida and Y. Hatate: *Chemical Engineering* (in Japanese), (11), 46-51 (1992)
5) Johnson, E.P.: *Chem. Engng*, **89**, 39-44 (1982)
6) Nack, H., G.W. Felton and K.T. Liu: *Proc. of 5th Int. Conf. on Fluidized Bed Combustion*, Washington, D.C., **3**, 223 (1977)
7) Nakamura, K. and C.E. Capes: *Fluidization Technology II*, p. 159-184, Hem: sphere (1976)
8) Nowak, W., H. Mineo, R. Yamazaki and K. Yoshida: *Circulating Fluidized Bed Technology III*, p. 219-224, Pergamon Press, Oxford (1990)