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TAKEOVER VELOCITY IN A GAS-SOLID FLUIDIZED BED WITH BINARY SOLIDS

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ABSTRACT

The effects of volume ratio and particle size distribution of binary solids, fine and large particles, and superficial gas velocity on solid mixing and segregation were studied in a gas-solid fluidized bed. Takeover velocity, since it affects the fluidization characteristics in a gas-solid fluidized bed with binary solids, should be determined considering particle size distribution and bed composition.

INTRODUCTION

The most outstanding characteristics in a gas-solid fluidized bed with binary solids are segregation and solid mixing, which depends on differences in size, the density of binary solids and in the superficial gas velocity [1-4]. Therefore, to analyze gas-solid fluidized beds with binary solids, the degree of these properties should be evaluated. In spite of decades of research, a mechanism for solid mixing and segregation in gas-solid fluidized beds with binary solids has not been elucidated. Previous researchers have suggested an empirical correlation of mixed conditions in beds in order to show the fluidization features of gas-solid fluidized beds with binary solids. The following (1) is a typical Eq. proposed by Nienow *et al*. [5].

$$M = \frac{X_j}{\overline{\overline{X_J}}} = (1 + e^{-F})^{-1} \quad (1)$$

$$F = \left(\frac{U_0 - U_{TO}}{U_0 - U_{mfF}}\right)\exp(U_0 / U_{To}) \quad (2)$$

This equation was empirically proposed on the assumption that the composition of the top of the bed is axially constant, while the bottom where heavy particles sink shows a segregation pattern. Therefore, $\overline{X_J}$ defined as solid mixing index, $M = \frac{X_j}{\overline{\overline{X_J}}}$, represents the average composition and X_J denotes the composition of the top of the bed. Takeover velocity is the superficial gas velocity at which the gas-solid fluidized bed with binary solids is transformed from segregated to a solid mixing region. However, empirical Eqs. (1) and (2) cannot be applied to all experimental results because they were proposed under limited experimental conditions; i.e., 0.5>jetsam volume fraction and 3> particle size ratio of flotsam to jetsam. In addition, Eq. (1) is the quantitative equation showing the state of solid mixing of gas-solid fluidized beds with binary solids under a limited segregation pattern. However, the segregation in such beds goes through various patterns. Thus, in this study, the solid mixing index and the takeover velocity, playing important roles in a gas-solid fluidized bed with binary solids as hydrodynamic features, are to be explored and the fluidization features in these beds are to be evaluated using the relation between the solid mixing index and the takeover velocity. It is expected that these findings will provide important information for the research of hydrodynamic features of multi-component solid particles and for prediction of its operating conditions.

EXPERIMENT

The binary solids used in this experiment are glass beads (flotsam) and zirconia beads (jetsam) and their physical properties are summarized in Table 1.

Figure 1 shows the schematic diagram of the gas-solid fluidized bed with binary solids used. In the case of the bed with binary solids, the pressure difference and minimum fluidization velocity were determined when the particle size distribution and volume ratio of flotsam to jetsam were changed. Samples of constant volume were collected through the sampling tube at intervals of 0.05m starting 0.05m above the distributor at the column. The samples were used to evaluate the axial composition in the bed. Generally, beds expand if the superficial gas velocity in a gas-solid fluidized bed is increased and the weight of solid particles equals the drag forces exerted by the gas at a certain superficial gas velocity, i.e., the minimum fluidizing velocity (U_{mf}). The following equations show the minimum fluidization conditions [4].

$$\frac{\Delta P_b}{L_{mf}} = (1-\varepsilon_{mf})(\rho_s - \rho_f)\frac{g}{g_c} \tag{3}$$

$$1 = \varepsilon_{mf} + \varepsilon_F + \varepsilon_J \tag{4}$$

$$\varepsilon_F = \frac{M_F / \rho_F}{A \times L_{mf}} \tag{5}$$

$$\varepsilon_J = \frac{M_J / \rho_J}{A \times L_{mf}} \tag{6}$$

The minimum fluidizing velocity in a binary system can be predicted from Eqs. (7)-(9) presented by Goossens *et al.* [6].

$$\frac{\overline{d_p} U_{mf} \rho_f}{\mu} = [(33.7)^2 + 0.0408 \frac{\overline{d_p}^3 \rho_f (\overline{\rho_p} - \rho_f)}{\mu^2}]^{\frac{1}{2}} - 33.7 \tag{7}$$

Where

$$\frac{1}{\overline{\rho_p}} = \frac{\overline{x_F}}{\rho_F} + \frac{(1-\overline{x_F})}{\rho_J} \tag{8}$$

$$\frac{1}{\overline{d_p \rho_p}} = \frac{\overline{x_F}}{\rho_F \times d_F} + \frac{\overline{x_J}}{\rho_J \times d_J} \tag{9}$$

To predict the minimum fluidizing velocity for binary solids, they applied the average values of $\overline{d_p}$, $\overline{\rho_P}$, calculated by Eqs. (8) and (9), to Eq. (7) proposed by Wen and Yu [7] showing the measurement of that velocity in a single particle.

Brereton and Grace [8] defined the solid mixing index as the following Eqs. (10)-(14) in order to investigate the change of the degree of solid mixing in the bed by superficial gas velocity and bed height when the initial volume ratio of the two solids in the bed was $\overline{X_F} : \overline{X_J}$.

$$\gamma = \sigma / \sigma_{fs} \tag{10}$$

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_{Ji} - \overline{x_J})^2} \tag{11}$$

$$\overline{X_J} = \frac{1}{N}\sum_{i=1}^{N} X_{Ji} \tag{12}$$

$$\sigma_{fs} = \sqrt{\overline{X_J}(1 - \overline{X_J})} \tag{13}$$

$$M_I = 1 - \gamma = 1 - \sigma / \sigma_{fs} \tag{14}$$

The segregation index (γ) is the ratio of the standard deviation (σ) of the composition (X_J) in the bed at each height to that (σ_{fs}) of the composition (X_J) in the bed segregated completely from the average composition ($\overline{X_J}$) of jetsam. The sum of the segregation index and solid mixing index (M_I) is 1; solid mixing is dominant as the solid mixing index approaches 1, whereas segregation is serious as the index approaches 0. The superficial gas velocity at which the fluidization feature in a bed is changed from solid mixing to segregation is called the takeover velocity. That is, the segregation in a bed takes place at the superficial gas velocity below takeover velocity.

RESULTS AND DISCUSSION

Flow characteristics of a binary system – effect of particle size distribution

Figure 2 shows the change of differential pressure as a function of superficial gas velocity for different volume ratios and particle size distributions of binary solids. It was confirmed that the minimum fluidizing velocity of binary solids in both systems of broad and narrow particle size distribution appeared between those of each single solid. In the system with a broad particle size distribution, segregation was not observed clearly and the smooth curve of differential pressure dominated by fixed and fluidized beds was shown, which was similar to that in the system of broad particle size distribution (BPSD) of a single solid reported by Chew *et al.* [9] and Gauthier *et al*. [10]. Conversely, transient regions showing segregation were observed in the system of narrow particle size distribution (NPSD). The segregation appears in the system of NPSD since such a system consists of extreme-sized particles compared to the system of a BPSD.

Flow characteristics of a binary system – effect of flotsam particles

Figure 3 shows the change in the minimum fluidizing velocity as determined by differential pressure according to the volume ratio of the two solids in the bed. The minimum fluidizing velocity decreased as the volume fraction of the flotsam increased. In addition, it was found that these experimental results were similar to that of the minimum fluidizing velocity in a binary solid system calculated by Eqs. (7)-(9) proposed by Goossens *et al*. [6]. The reason these results are congruent is that agglomerate particles are formed by inter-particle forces among fine and large particles. The increase in the volume fraction of fine particles in the bed causes the alteration of particle arrangement and the voidage is eventually changed. it can be found that the reason for the sharp decrease in the minimum fluidizing velocity with the increase in volume fraction of fine particles is related to the voidage in the bed [11].

The obtained voidage values and those calculated by Eqs. (5) and (6) under the condition of minimum fluidization are presented in Figure 4. The void in the bed was reduced until the volume fraction of flotsam was 0.4, and then the void in the bed was increased over the volume fraction of flotsam. Therefore, the reduction of the void in the bed causes the actual superficial gas velocity to increase and thereby the drag force becomes stronger, which decreases the minimum fluidizing velocity.

Flow characteristics of a binary system– solid mixing index and takeover velocity

Figure 5 shows the change of axial solid composition in the bed by superficial gas velocity when the volume ratio of the two solids was 0.6:0.4. The composition was not different from the initial composition at the superficial gas velocity over takeover velocity. Additionally, the composition of each flotsam and jetsam was large at both the top and bottom of the bed, respectively, at the velocity below the takeover velocity, thereby causing segregation.

Figure 6 presents the change of the solid mixing index by superficial gas velocity together with differential pressure to determine the degree of solid mixing according to the fluidization region in the gas-solid fluidized bed with binary solids. In this figure, the solid mixing index was close to 1 in the fully fluidized region and decreased as the fluidization region was changed from transient to fixed. This indicates that the fluidization of binary solids in the bed was changed from solid mixing to segregation at a certain superficial gas velocity. The certain superficial gas velocity was defined as the takeover velocity.

The values of the solid mixing indices calculated by Eqs. (1) and (14) according to the initial volume ratio of the two solids are shown in Figure 7. Both solid mixing indices were almost 1 at high superficial gas velocity, but decreased when the velocity was below the takeover velocity. In the transient region where the segregation takes place, there was a difference in the values of both solid mixing indices. The solid mixing index is the value that is calculated using the composition of the bed. The reason why the solid mixing index calculated by Nienow *et al.* [1] is different from that calculated by Brereton and Grace [8] in the transient region is because they differed in the way they determined the composition in the gas-solid fluidized bed with binary solids. The former used the composition at the top of the bed as the standard and the latter used the axial composition. The decrease in the values of the solid mixing index in the narrow range of superficial gas velocity is due to the system of BPSD where the transient region is not clearly distinguished (Figure 7(a)). On the other hand, since the transition region is clear in the system of NPSD, the range of superficial gas velocity where segregation takes place can be distinguished (Figure 7(b)).

Figure 8 shows the variation of the Relative Standard Deviation (RSD) of the pressure fluctuation with superficial gas velocity at each bed height under the condition of fixing all the experimental parameters. RDS means standard deviation divided by the mean of the pressure fluctuation. In the fixed region and fluidized region, RSD values showed a certain tendency, while they did not show any pattern in the transient region, indicating that the composition in the bed was changed from bottom to top with the bed height. Therefore, the takeover velocity was decided by the solid mixing index that was calculated by Brereton and Grace [8], using the standard deviation to consider solid composition at each different bed height. Namely, the superficial gas velocity where the state of solid mixing was changed into that of segregation, decided by plotting each region where the solid mixing index was constant and decreased, was decided as the takeover velocity.

Flow regime of the binary system

The variations of minimum fluidizing velocity and takeover velocity with the volume fraction of jetsam are shown in Figure 9. The fluidization region could be classified into fixed, transient and fully fluidized regions by the relationship between the minimum flow velocity and the takeover velocity. A fixed bed where both solids do not flow was formed in the fixed region ($U_0 < U_{mf}$). In the transient region ($U_{mf} < U_0 < U_{TO}$), segregation, in which some solids are not fluidized and heavy particles sink to the bottom, was confirmed. The state of solid mixing, in which particles are fluidized well, was found in the fully fluidized region ($U_{To} < U_0$). Formisani *et al.* [11] studied the effect of flotsam on fluidization in gas-solid fluidized beds with binary solids by deciding the minimum flow velocity and fully fluidized velocity through the measurement of differential pressure. They reported that the transient region was decreased with the increase in the volume fraction of flotsam, which was the same as the result in our study. In addition, the system of small voidage in the bed or BPSD was observed in a small part of the transient region ($U_{mf} < U_0 < U_{TO}$), unlike the system of binary solids with NPSD

CONCLUSION

In this study, the following conclusions could be described through the experiments related to actual fluidization characteristics of gas-solid fluidized beds with binary solids:

1) In the binary system, the fluidization region was classified into a fixed ($U_0 < U_{mf}$), transient ($U_{mf} < U_0 < U_{TO}$) and fully fluidized region ($U_{To} < U_0$) according to the fluidization feature.
2) From the decision of solid mixing index and takeover velocity through the consideration of axial change of segregation pattern in gas-solid fluidized beds with binary solids, uniform solid mixing could be seen above the takeover velocity and partial segregation below the takeover velocity.
3) In gas-solid fluidized beds with binary solids containing fine particles, the voidage in beds showed a low value at a flotsam volume fraction of 0.4, and the minimum fluidizing velocity decreased sharply up to that fraction. Conversely, the takeover velocity in the jetsam rich system (0.2:0.8) was relatively larger than that in the flotsam rich system (0.8:0.2).
4) Segregation should be decreased if the volume fraction of fine particles and the width of particle size distribution in the system were increased.

NOMENCLATURE

d_c, d_f	Diameter of coarse and fine particle	$\overline{d_p}$	average particle diameter
$\overline{\rho_p}$	average particle density of a mixture	ΔP_b	differential pressure across the bed
g	acceleration of gravity	ε_g, ε_s	holdup of gas, solid
L_{mf}	height of bed at minimum fluidization	ε_{mf}	voidage in a bed at minimum fluidizing conditions
M	solid mixing index	ρ_g,ρ_f, ρ_j,ρ_s	density of gas, floatsam, jetsam, solid
U_{mf}, U_{mfF}, U_{mfJ}	minimum fluidizing velocity of binary particle, floatsam, jetsam of system.	σ	standard deviation
U_{To}	takeover velocity	σ_{fs}	value of σ corresponding to full segregation

X_J, X_F	volume fraction of jetsam, floatsam	γ	segregation index
$\overline{x_j}$, $\overline{x_f}$	average volume fraction of jetsam, floatsam		

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Table 1. Physical properties of the particles used

	Material	Mean diameter [μm]	True density [kg/m^3]	Standard deviation [μm]
Broad particle size distribution	Coarse particle (Gb421) (100~710μm)	421	2,339	201
	Fine particle (Zr51) (0~125μm)	51	3,726	356
Narrow particle size distribution	Coarse particle (Gb390) (355~425 μm)	390	2,339	0
	Fine particle (Zr58) (53~63μm)	58	3,726	0

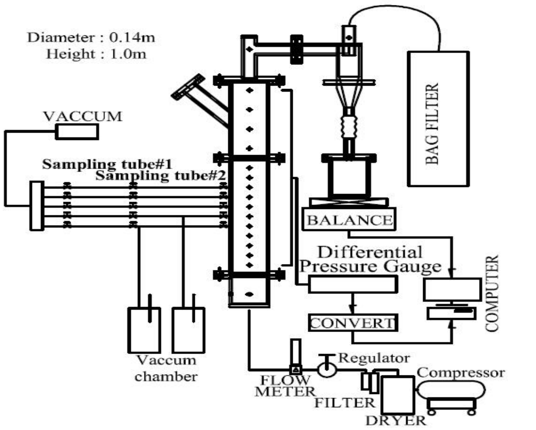

Fig. 1 Schematic diagram of experimental apparatus

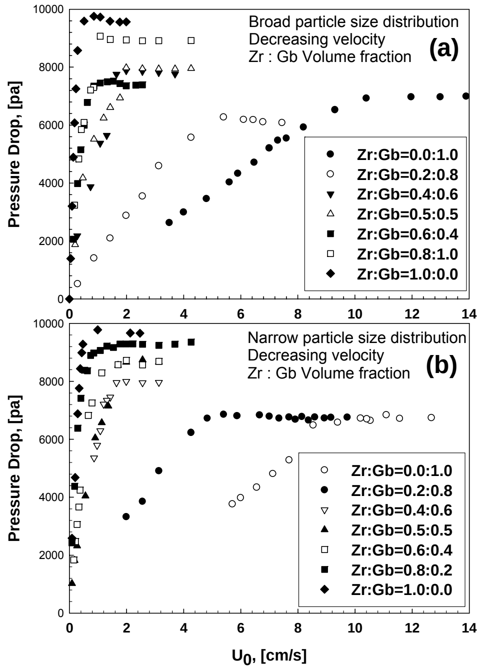

Fig. 2 Differential pressure vs. superficial gas velocity of (a) Binary solids with broad particle size distribution and (b) Binary solids with narrow particle size distribution.

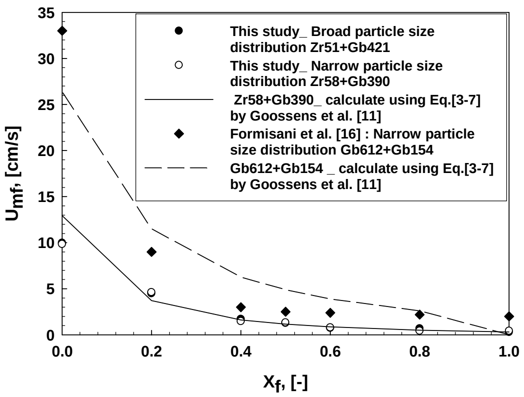

Fig. 3 Minimum fluidizing velocity of two solids at the minimum fluidized bed vs. flotsam volume fraction.

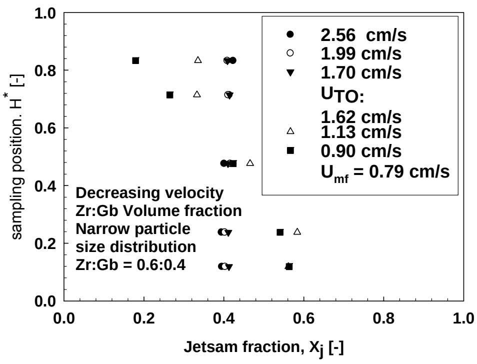

Fig. 5 The effect of superficial gas velocity on the volume fraction of jetsam with axial bed height

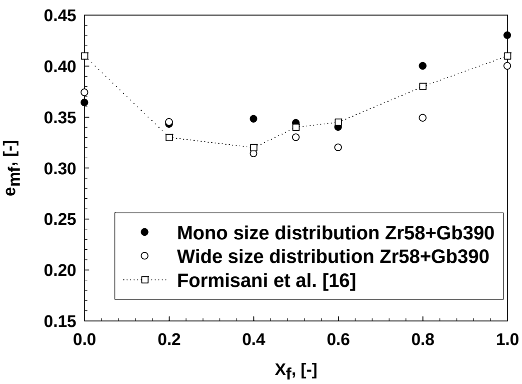

Fig. 4 Voidage at minimum fluidization vs. flotsam volume fraction.

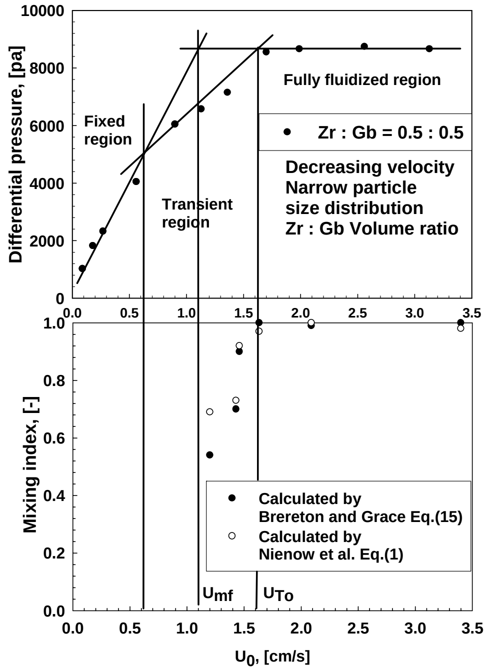

Fig. 6 Fluidization region according to superficial gas velocity.

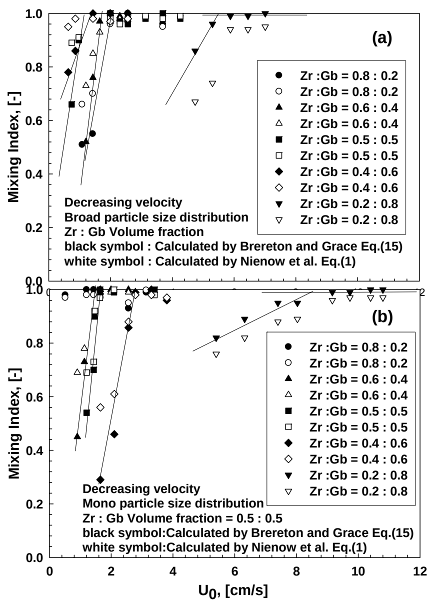

Fig. 7 Solid mixing index according to decreasing superficial gas velocity of (a) Broad particle size distribution and (b) Narrow particle size distribution

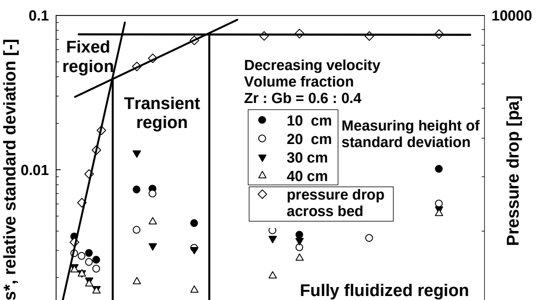

Fig. 8 Relative standard deviation according to bed height in the fluidization region.

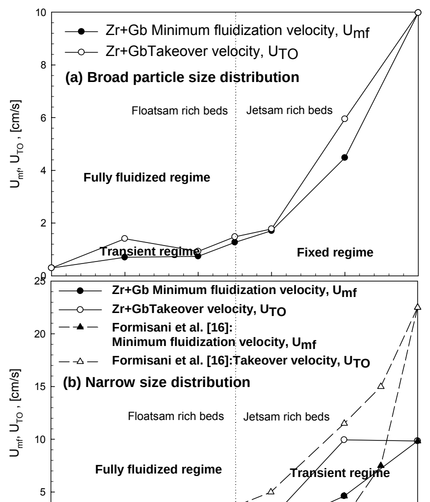

Fig. 9 Fluidization regime of (a) Binary solids with broad particle size distribution and (b) Binary solids with narrow particle size distribution.