PARTICLE HOLD-UP AND ELUTRIATION RATE IN THE FREEBOARD OF FLUID BEDS

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Based on experimental results from three fluid beds of different cross sections (15 × 15 cm, 8 × 8 cm and 7.1 cm i.d.), the effects of superficial gas velocity, freeboard height, cross sectional area and particle properties on the axial particle hold-up distribution in the freeboard and the elutriation rate from the top of the column were investigated. An entrainment intensity R was proposed for the particles to explain the effect of size distribution and density on the particle hold-up. The particle hold-up was found proportional to $R^{1.87}$, and increased with increasing freeboard height and cross-sectional area. Empirical equations for both the particle hold-up distribution and for the particle elutriation rate were obtained.

Introduction

Fluid-bed reactors, in which Geldart's A particles[2] were fluidized, have been applied to many industrial processes such as fluid catalytic cracking (FCC) and acrylonitrile synthesis. In such fluid-bed reactors, particle hold-up in the freeboard and particle elutriation rate are very large. Quantitative considerations regarding particle hold-up in the freeboard and particle elutriation rate are necessary in designing and operating a fluid-bed reactor because of the significant contribution of the particles in the freeboard to chemical reactions[1, 8] and temperature distribution[8]. However, only a few investigations to quantify the particle hold-up in the freeboard have been carried out, and the effects of particle properties, column size and operation conditions on particle hold-up in the freeboard have not yet been made clear.

Several studies have drawn attention to the behavior of solid particles suspended in the freeboard[3-5, 7, 9-11]. The important roles of (1) bubble eruption at the bed surface on particle ejection[3, 11], (2) lateral particle transport from the particle-ascending zone to the particle-descending zone on the axial particle hold-up profiles, and (3) fluctuation of gas in lateral particle transport on the mechanism of entrainment, have been pointed out. The equations proposed to estimate the particle hold-up in a freeboard describe particle hold-up decreasing exponentially with height above the bed surface[4, 9]. Particle-descending flow near the wall was confirmed by using optical probes by Morooka *et al.*[9]

In this study, axial particle hold-up distribution in a freeboard of fluid bed was measured by using columns of three different cross-sections. Effects of gas velocity, height of freeboard, particle properties and cross-sectional area on particle hold-up in the freeboard and the elutriation rate were investigated. Based on the experimental results, empirical equations for particle hold-up, elutriation rate and elutriation rate constant were obtained.

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1. Experimental

Figure 1 shows a schematic diagram of the experimental apparatus. Three acrylic resin columns of different cross-sections, 15 × 15 cm, 8 × 8 cm and 7.1 cm i.d., were used for the fluid beds. The details of each column are shown in **Table 1**. Two types of caps were used for the column of 15 × 15 cm cross-section. For each column, the column height was changed from 1 m to 3 m by adding pieces of 0.5 m length each. A perforated acrylic plate with 1 % opening (holes of 1 mm diameter with 8.35 mm pitch) was used as a gas distributor for each column. Air from a compressor was fed to the bottom of the column through an oil filter and a silica gel tower. The air flow rate was measured by an orifice meter. The particles entrained from the column were separated from gas by a cyclone and returned into the dense bed. After steady particle circulation through the column and the cyclone was established, the pressure-drop profile along the height was measured with a micro-manometer (SHIBATA, ISP-3) of 0.01 mm H_2O accuracy. The axial particle hold-up distribution in the freeboard was obtained from the pressure-drop profile, based on the following relationship.

$$1 - \varepsilon = \Delta P / ((\rho_p - \rho_g)\, g\, \Delta Z) \tag{1}$$

The elutriation rate was measured by weighing the

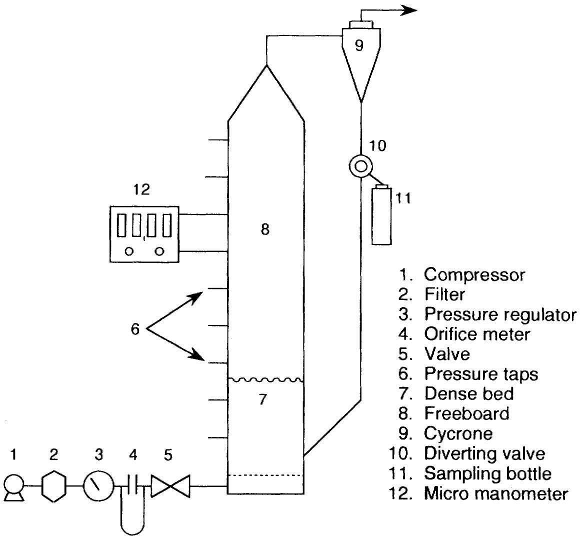

Fig. 1 Experimental apparatus

Table 1. Details of the columns

Column	Height [m]	Cross-section	Gas distributor	Top
1	1, 1.5, 2, 2.5, 3	0.071 m i.d., 0.0040 m²	Perforated plate 1 % opening	Conical cap of 60-degree angle
2	1, 1.5, 2, 2.5, 3	0.08 × 0.08 m, 0.0064 m²	Perforated plate 1 % opening	A*
3	1, 1.5, 2, 2.5, 3	0.15 × 0.15 m, 0.0225 m²	Perforated plate 1 % opening	A* and B*

A* Pyramidal cap of 60-degree angle (A: 60 deg.)
B* Cubic cap with gas exit on a side (B)

particles collected for a period in the sampling vessel below the cyclone. The size distribution of the bed particles and the elutriated particles was obtained with JIS standard sieves.

Five kinds of particles of different average diameter and different particle density were used as bed material in this experiment. Each kind of particles belongs to group A in Geldart's classification[2]. Size distribution and calculated terminal velocity of the particles are shown in **Table 2**.

The static bed height L_{mf} was almost 0.30 m in this experiment. It was difficult to measure the fluidizing bed height L_f accurately because of the intense bubble eruption at the surface. Therefore, L_f was calculated by using the following equation from Kato[6].

$$(L_f - L_{mf}) / L_{mf} = 0.549\, U_{mf}^{0.58} \left((U_0 - U_{mf}) / U_{mf}\right)^a$$
$$a = 0.483\, D_e^{-0.12} \qquad (2)$$

2. Results and Discussion

2.1 Effects of various factors on the axial particle hold-up distribution in the freeboard

1) Effect of superficial gas velocity and particles **Figure 2** shows the particle hold-up distribution at various superficial gas velocities obtained for FCC-1 and MSC-1 by using the column of A_t = 0.0040 m² (7.1 cm i.d. tube) and H = 2.64 m. The particle hold-up increased with increasing gas velocity and decreased with increasing height above the bed surface (Z-L_f). When the gas velocity was as low as 0.1 m/s and 0.2 m/s, the transport disengaging height, TDH, was around (Z-L_f) = 1 m for both FCC-1 and MSC-1. On the other hand, when the gas velocity was higher than 0.3 m/s, TDH did not appear within the freeboard height of H = 2.64 m. The

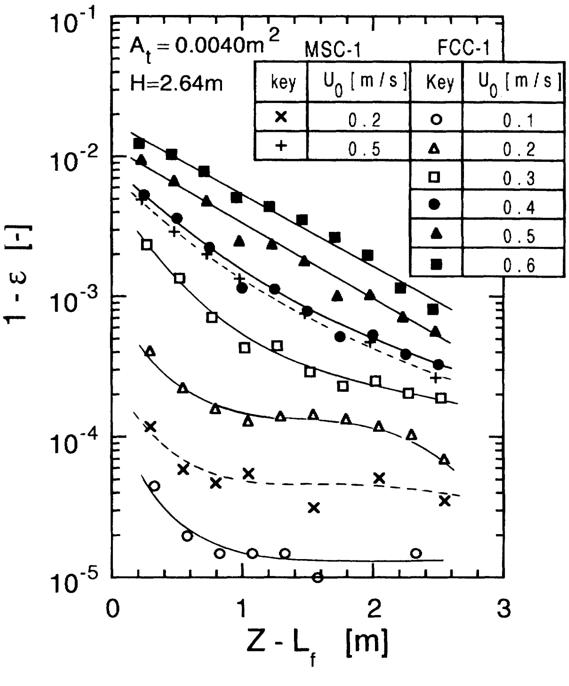

Fig. 2 Effect of gas velocity on the axial particle hold-up distribution in the freeboard for bed materials of FCC-1 and MSC-1

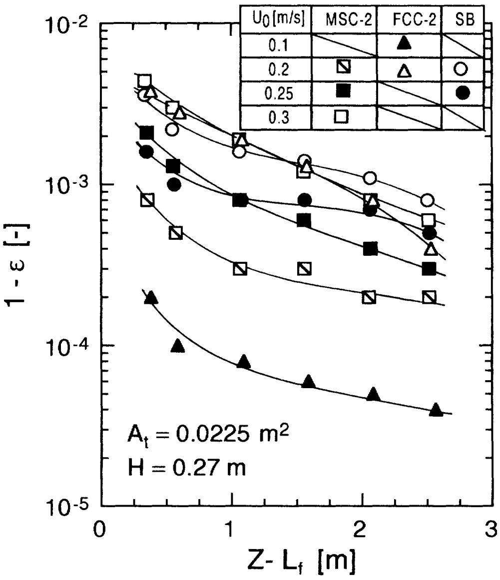

Fig. 3 Axial particle hold-up distributions obtained for MSC-2, FCC-2, and SB at various gas velocities

Table 2. Properties of particles used in this experiment

	FCC-1		FCC-2		Activated alumina (MSC-1)		Activated alumina (MSC-2)			Silica balloon (SB)	
ρ_p [kg/m^3]	1340		1050		1700		1680			230	
dp [μm]	64		51.1		64		52.9			182	
dp_i [μm]	ΣX_i [-]	Ut_i [m/s]	ΣX_i [-]	Ut_i [m/s]	ΣX_i [-]	Ut_i [m/s]	ΣX_i [-]	Ut_i [m/s]	dp_i [μm]	ΣX_i [-]	Ut_i [m/s]
30.0	0.022	0.035	0.049	0.029	0.014	0.045	0.044	0.046	50.5	0.006	0.018
41.5	0.084	0.068	0.159	0.055	0.061	0.086	0.181	0.088	76.5	0.023	0.041
49.0	0.323	0.094	0.458	0.076	0.263	0.119	0.531	0.122	107.5	0.151	0.080
58.0	0.431	0.132	0.634	0.107	0.405	0.167	0.724	0.171	137.5	0.272	0.131
69.0	0.647	0.187	0.913	0.151	0.704	0.237	0.939	0.242	163.5	0.404	0.185
82.5	0.742	0.267	0.965	0.216	0.851	0.339	0.951	0.346	193.5	0.518	0.259
107.5	0.991	0.453	1.000	0.367	0.997	0.575	0.980	0.587	253.5	0.794	0.445
137.5	0.998	0.709	-	-	0.999	0.830	0.990	0.961	323.5	0.897	0.725
165.0	1.000	0.850	-	-	1.000	0.997	1.000	1.383	385	0.971	1.027
									505	1.000	1.776

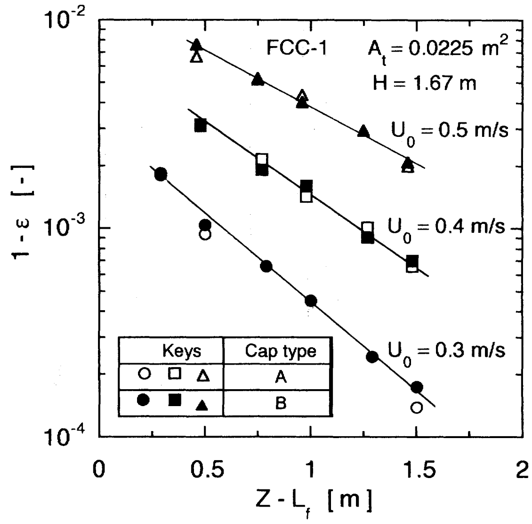

Fig. 4 Axial particle hold-up distributions obtained by different types of column cap

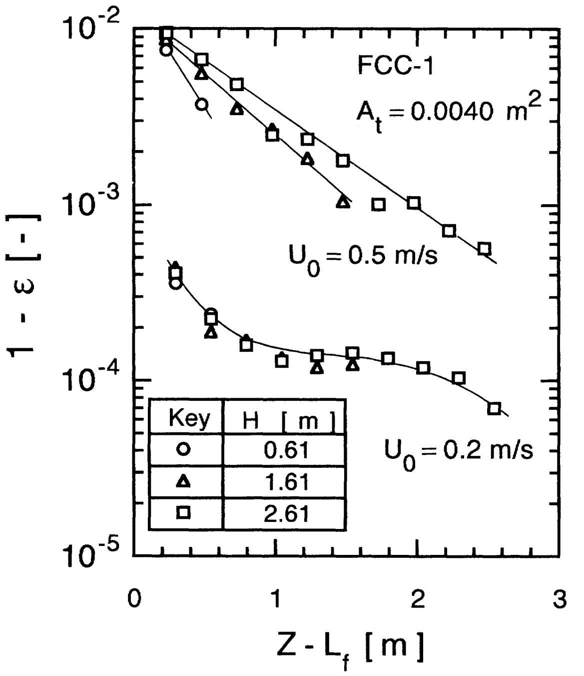

Fig. 5 Effect of freeboard height on the axial particle hold-up distribution in the freeboard at U_0 = 0.2 m/s and 0.5 m/s

curve of the axial particle hold-up distribution changed with the gas velocity and became a straight line when the gas velocity was over 0.5 m/s, suggesting that the particle hold-up decreased exponentially with (Z-L_f).

Particle hold-up of MSC-1 was almost 30 % larger than that of FCC-1 at the same gas velocity. The particle density of MSC-1 was almost 30 % larger than that of FCC-1 while both were the same in average size as shown in Table 2. Smaller particle density brought about larger particle hold-up.

Figure 3 shows the effects of gas velocity on the axial particle hold-up obtained for MSC-2, FCC-2 and SB. Since the particle size distribution and density were different for each bed material, absolute values of the particle hold-up were different.

2) Effect of the type of column cap **Figure 4** shows the axial particle hold-up distributions obtained for the column using different types of column cap as shown in Table 1. The particle hold-up distribution was almost the same for each type of cap. As shown in this figure, the particle hold-up was not affected by the type of column cap in this experiment.

3) Effect of freeboard height **Figure 5** shows the effect of freeboard height on the particle hold-up distribution. When the gas velocity was as low as 0.2 m/s, the particle hold-up was hardly affected by freeboard height. When the gas velocity was high enough, say 0.5 m/s, since TDH did not appear below the freeboard height, the particle hold-up at the same freeboard height increased with increasing freeboard height. It is considered that the particle transfer from the particle-ascending zone to the particle-descending zone at the same axial position increased with increasing freeboard height.

4) Effect of cross-sectional area of the column **Figure 6** shows the particle hold-up distributions obtained for different cross-sectional columns. It was found that the particle hold-up increased with increasing cross-sectional

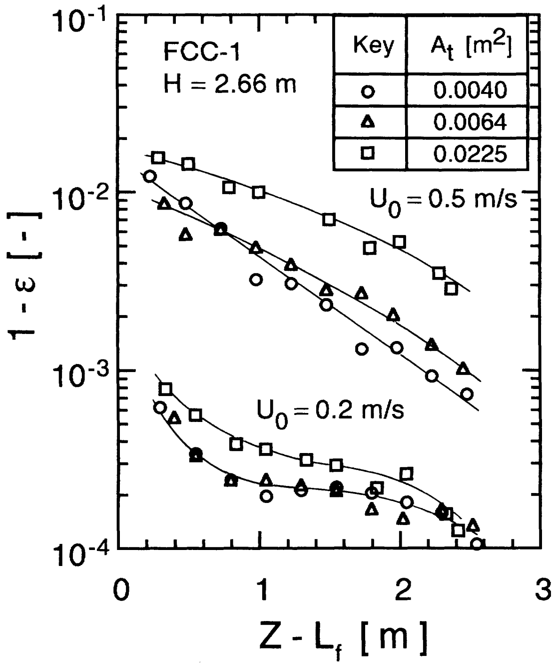

Fig. 6 Effect of cross-sectional area on the axial particle hold-up distribution in the freeboard at U_0 = 0.2 m/s and 0.5 m/s

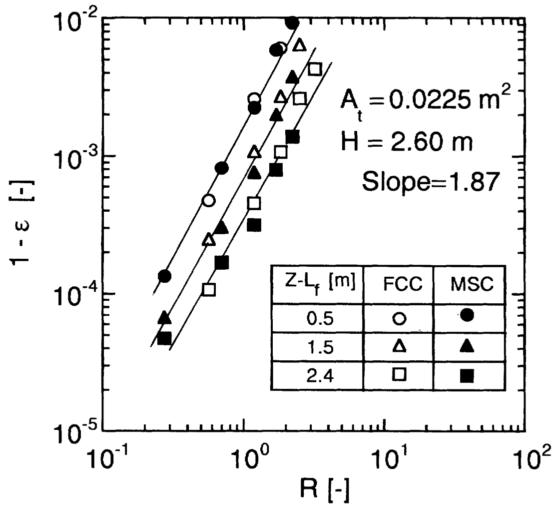

Fig. 7 Relationship between dimensionless factor R and (1-ε) for FCC-1 and MSC-1

area regardless of gas velocity. It is considered that particles ejected from the bed by bubble eruption at the bed surface were increased with increasing bubble diameter[3] in this experiment. Also, the internal circulation of particles in the freeboard might be increased with increasing cross-sectional area.

2.2 Equation for axial particle hold-up distribution in the freeboard

As shown above, the effects of various factors on particle hold-up distribution were clarified experimentally. Empirical equations are proposed below for estimating particle hold-up and particle elutriation.

The slip velocity, the difference between the gas

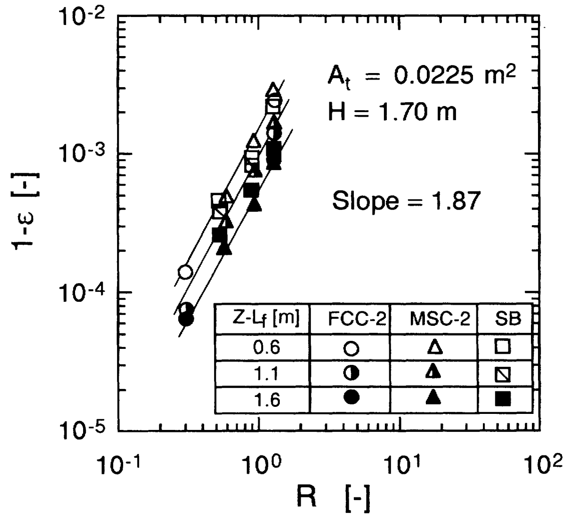

Fig. 8 Relationship between dimensionless factor R and (1-ε) for FCC-2, MSC-2 and SB

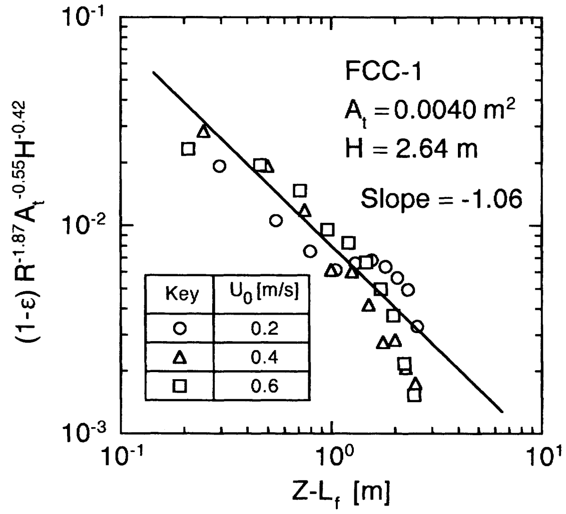

Fig. 9 Relationship between $(1\text{-}\varepsilon)\cdot R^{-1.87}\cdot A_t^{-0.55}\cdot H^{-0.42}$ and $(Z\text{-}L_f)$

velocity and the terminal particle velocity, is believed to be the most important determining factor for particle hold-up in the freeboard. To evaluate particle hold-up precisely, the size distribution of the particles should be taken into account, because the terminal particle velocity is largely dependent on particle size. We propose a dimensionless factor R which expresses the entrainment intensity of particles concerning their size distribution as follows:

$$R = \sum_j (X_i (U_0 - U_{ti}) / U_{ti}), \quad U_{ti} < U_0 \tag{3}$$

where the subscript i stands for the size of a particle. **Figures 7** and **8** show the relation between R and the particle hold-up in the freeboard. The particle hold-up for particles of different size distributions and different particle densities is expressed as a function of R and the hold-up is proportional to $R^{1.87}$. The particle hold-up is strongly dependent on R. From these figures, it is found that the entrainment intensity R is a useful factor for

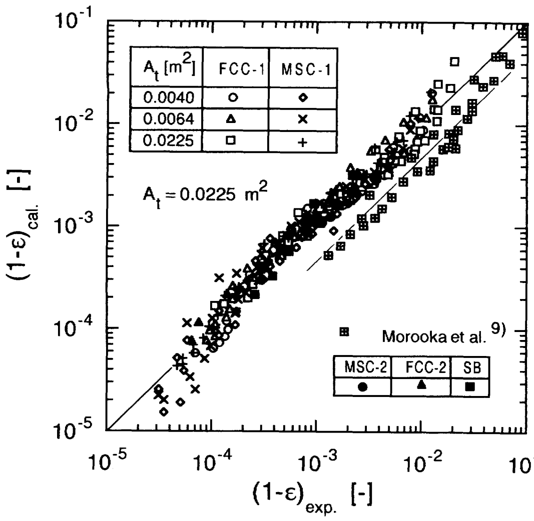

Fig. 10 Comparison between (1-ε) obtained experimentally and that of calculated from Eq. (4)

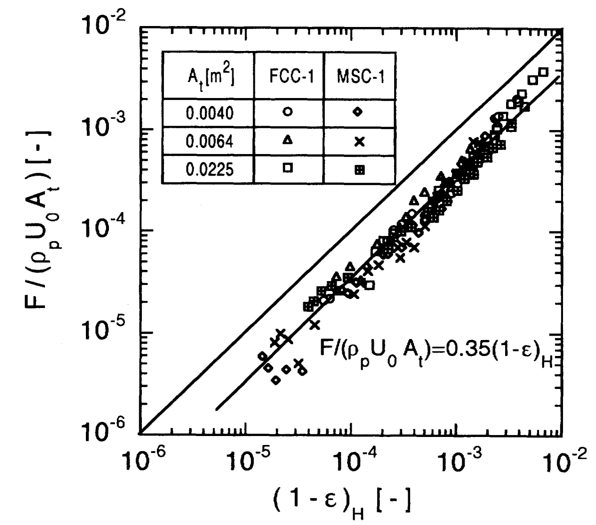

Fig. 11 Comparison between $(1\text{-}\varepsilon)_H$ and $F/(\rho_p{\cdot}U_0{\cdot}A_t)$

expressing the intensity of entrainment for particles.

For the other factors, i.e., cross-sectional area A_t, freeboard height H and height above the bed surface (Z-L_f), curve-fitting was carried out using the experimental results, and it was found that the particle hold-up was proportional to the product $A_t^{0.55}$ $H^{0.42}$. **Figure 9** shows the relationship between Z-L_f and (1-ε) $R^{-1.87}$ $A_t^{-0.55}$ $H^{-0.42}$. In the freeboard, the particle hold-up, (1-ε), was proportional to $(Z\text{-}L_f)^{-1.06}$. Therefore, the following empirical equation for particle hold-up in the freeboard is proposed.

$$1-\varepsilon = 7.41\times10^{-3}\,R^{1.87}\,A_t^{0.55}\,H^{0.42}\,(Z-L_f)^{-1.06} \quad (4)$$

The application range of Eq. (4) should be as follows.

$$0.2\,m/s \le U_f \le 0.6\,m/s,\quad 0.004\,m^2 \le A_t \le 0.0225\,m^2$$

Correlation between the particle hold-up obtained by the experiment and that calculated by Eq. (4) is shown in **Fig. 10**. The obtained empirical equation expressed the particle hold-up in the freeboard within +100 %/–50 % deviation. Particle hold-up of FCC in a freeboard obtained by Morooka *et al.*[9] was also correlated by Eq. (4) and is also shown in the figure. Those calculated are almost 50 % as large as those obtained.

2.3 Equation for the elutriation rate

The elutriation rate F is related to the particle hold-up at the top of the freeboard $(1\text{-}\varepsilon)_H$ as follows.

$$F = (1-\varepsilon)_H\,\rho_p\,U_{pH}\,A_t \quad (5)$$

where U_{pH} is the particle velocity at the top of the freeboard. $(1\text{-}\varepsilon)_H$ is obtained by substituting H for (Z-L_f) in Eq. (4). **Figure 11** shows a comparison between $(1\text{-}\varepsilon)_H$ and $F/(\rho_p\,U_0\,A_t)$. $F/(\rho_p\,U_0\,A_t)$ was almost 0.35 times as large as $(1\text{-}\varepsilon)_{H\,cal}$, suggesting that U_{pH} corresponded to 0.35 U_0. From this result, the following equation was derived instead of Eq.(5), and can be used to estimate the elutriation rate:

$$F = 0.35\,(1-\varepsilon)_H\,\rho_p\,U_0\,A_t \quad (6)$$

The application range of Eq. (6) is the same as that of Eq.(4)

Conclusions

A comprehensive experiment, using three different fluid beds and five kinds of particles, was carried out to investigate particle hold-up and elutriation in the freeboard. The following results were obtained.

(1) The particle hold-up distribution was affected not only by superficial gas velocity and particle properties but also by the freeboard height and cross-sectional area of the column.

(2) An elutriation intensity R was proposed to express the particle hold-up of different particles, i.e., difference in size distribution and density.

(3) Empirical equations for the axial particle hold-up distribution in the freeboard, the elutriation rate and the elutriation rate constant were proposed.

Nomenclature

A_t	=	cross-sectional area of bed	[m^2]
D_e	=	hydraulic diameter	[m]
D_t	=	column diameter	[m]
d_p	=	particle diameter	[m]
d_{pi}	=	diameter of i-size particle	[m]
F	=	elutriation rate	[kg/s]
g	=	gravitational acceleration	[m/s^2]
H	=	freeboard height	[m]
K_i	=	elutriation rate constant of i-size particles based on unit cross-sectional area of bed	[kg/(m^2·s)]
L_f	=	expanded bed height	[m]
L_{mf}	=	bed height at minimum fluidizing gas velocity	[m/s]
R	=	entrainment intensity	[-]
U_0	=	superficial gas velocity	[m/s]
U_{mf}	=	minimum fluidizing gas velocity	[m/s]
U_t	=	terminal velocity	[m/s]
U_p	=	particle velocity	[m/s]
V	=	bed volume at fluidizing conditions	[m^3]
W	=	total weight of bed	[kg]

X_i	=	weight fraction of i-size particles in bed particles	[-]
Y_i	=	weight fraction of i-size particles in entrained particles	[-]
Z	=	height above bed surface	[m]
ΔP	=	axial pressure drop	[Pa]
ΔZ	=	distance between pressure taps	[m]
ε	=	void fraction	[-]
ρ_p	=	density of particles	[kg/m^3]
ρ_g	=	density of gas	[kg/m^3]

Literature Cited

1) Furusawa, T.: *Kagaku Kogaku*, **50**, 13 (1986)
2) Geldart, D.: *Powder Technol.*, **7**, 285-292 (1973)
3) Hatano, H. and M. Ishida: *Powder Technol.*, **35**, 201-209 (1983)
4) Horio, M., A. Taki, Y. S. Hsieh and I. Muchi: "Fluidization", ed. by Grace and Matsen, p. 509-518, Plenum Press (1980)
5) Iwasaki, M. and S. Tashiro: *Kagaku Kogaku*, **52**, 147-155 (1988)
6) Kato, K., M. Maeno and T. Takahashi: *Kagaku Kogaku Ronbunshu*, **6**, 522-526 (1980)
7) Kunii, D. and O. Levenspiel: *Powder Technol.*, **61**, 193-206 (1990)
8) Miyauchi, T. and S. Furusaki: *AIChE J.*, **20**, 1087-1096 (1974)
9) Morooka, S., K. Kawazuishi and Y. Kato: *Powder Technol.*, **26**, 75-82 (1980)
10) Nazemi, A., M. A. Bergougnou and C.G. Baker: *AIChE Symp. Ser.*,**70**, 98-102 (1974)
11) Zenz, F.A. and N.A. Weil: *AIChE J.*, **4**, 472-479 (1958)