THE EFFECT OF INTERNALS ON THE ELUTRIATION OF PARTICLES FROM FLUIDIZED BED

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The elutriation rate from the gas-solid fluidized bed with and without vertical multi-tube internals was measured by continuous steady state operation. The elutriation rate constant was not only affected by gas velocity, terminal velocity of particles and properties of gas, but also affected by hydraulic diameter of bed and the minimum fluidezed gas velocity. The empirical equations for elutriation rate constant were obtained.

1. Introduction

When particles with wide size distribution are fluidized, the fine particles are carried out from the fluidized bed with the gas stream.

There have been many works for the elutriation rate from an ordinary fluidized bed and many empirical equations to estimate the elutriation rate constant were proposed. But the most of the elutriation works were based on the experimental study obtained by batch operation and the particles with narrow size distribution. There are a few works to investigate the elutriation rate constant with wide size distribution of particles under the continuous steady state operation like actual comercial plant. Figure 1 shows the fluidized particle size used by the previous investigators in Geldart's classification map. The most of the previous investigators used group B particles.

In this study, to get more general and accurate quantitative knowledge on the elutriation of particles from a fluidized bed, the elutriation rate constants of several kinds of particles with different wide size distributions were measured by gas-solid fluidized bed with and without vertical multi-tube internals at continuous steady state operation. The effects of gas velocity, properties of gas and particle and the internals upon the elutriation rate constant were investigated. The empirical equations for the elutriation rate constant were obtained.

2. Experimental Apparatus and Procedure

Figure 2 shows a schematic diagram of the experimental apparatus. Acrylic resin column with 0.15 x 0.15 m rectangular cross section was used as fluidized bed. The particles elutriated from the bed were separated from gas by cyclons and

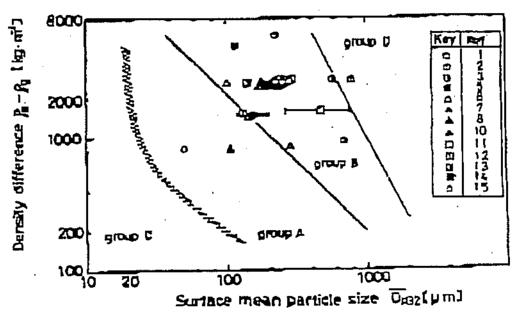


Fig. 1 The fluidized particle size used by the previous investigators

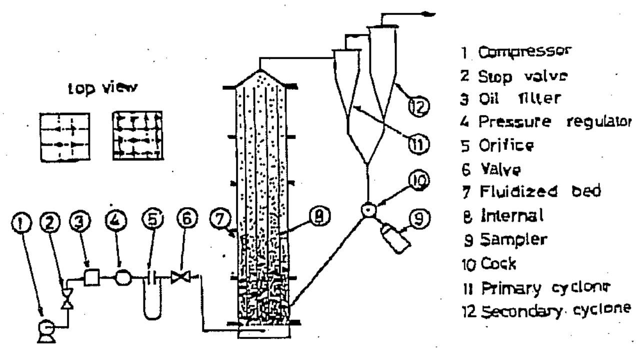


Fig.2 Experimental apparatus

returned into the dense bed as shown in Fig.2. The tubes made of poly vinyl chrolide, 1.8 or 2.6 cm diameter, were immersed vertically in the bed.

The hydraulic diameter De of bed is calculated as follows

$$De = \frac{4(Z^2 - ni\,\pi\,Di^2/4)}{4Z + ni\,\pi\,Di} \qquad (1)$$

Experimental procedure was as follows. When the elutriation reached the steady state, the weight of elutriated particles per constant time interval was measured. The size distribution of them was measured by JIS standard sieve and the size distribution of the bed particles was also measured simultaneously.

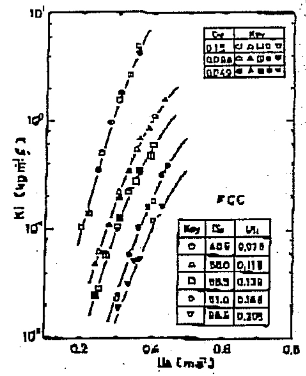


Fig.3 Relation between Ki and Ua for FCC particles.

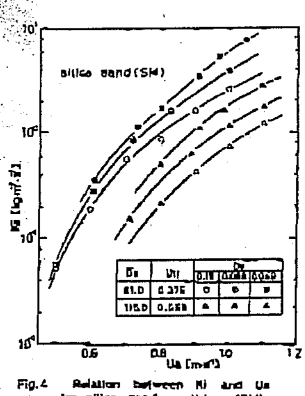


Fig.4 Relation between Ki and Ua for silica sand particles.(SM).

Table. 1 Properties and size distributions of fluidized particles

Dp [μm]	$\bar{D}_p$ [μm]	Silica sand (SF) Xi	Silica sand (SM) Xi	Silica sand (SC) Xi	Uti	FCC Xi	Uti	Glass beads (GF) Xi	Glass beads (GC) Xi	Uti
0- 37	30.0	0.122	–	–	0.121	0.069	0.081	0.003	–	0.118
37- 44	40.6	0.048		–	0.170	0.036	[illegible]	[illegible]	–	0.187
44- 53	48.2	0.038	–	–	0.208	0.209	0.094	0.041	–	0.250
53- 63	58.0	0.066	0.001		0.250	0.277	0.118	0.147	–	[illegible]
63- 74	68.5	0.080	0.070	–	0.310	0.062	0.132	0.103	–	0.340
74- 88	81.0	0.083	0.081	0.003	0.375	0.184	0.162	0.208	–	0.412
88-105	96.5	0.084	0.083	0.001	0.459	0.067	0.205	0.112	–	0.483
105-125	115.0	0.045	0.131	0.008	0.520	0.022	0.251	0.085	0.010	0.614
125-149	137.0	0.070	0.078	0.016	0.683	0.002	0.306	0.042	0.010	0.700
149-177	163.0	0.094	0.180	0.107	0.832	–	0.373	0.071	0.040	0.914
177-250	213.5	0.084	0.104	0.306	1.132	–	0.507	0.028	0.118	1.214
250-297	273.5	0.020	0.078	0.152	1.507	–	0.471	0.023	0.118	1.480
297-420	358.5	0.027	0.078	0.264	2.043	–	0.914	0.016	[illegible]	[illegible]
420-	420.0	0.022	0.018	0.137	2.318	–	1.032	–	0.006	2.071
Dp32		73.1	134.1	252.0		58.3		84.3	160.7	
Umf		0.0057	0.0164	[illegible]		0.00134		[illegible]	0.0214	

ρs: particle density [kg/m³] Uti: terminal velocity [m/s] Umf: minimum fluidization velocity [m/s]

Table 1 shows size distributions of particles used in this experiment. Solids particles used were silica sand, FCC and glass beads. Silica sand had three different size distributions such as fine(SF), middle(SM) and coarse(SC). Glass beads also had two size distribution such as fine(GF) and coarse(GC).

In this work, the elutriation rate constant Ki of each component particles in Table 1 is calculated as follows.

It is assumed that the elutriation rate of i-component particles is proportional to the concentration of i-component particles in the bed[9]. The elutriation rate constant Ki based on unit cross sectional area defined by Wen and Hassinger[14] is applied to calculate the rate constant. The following equation is obtained by the material balance of i-component particles at steady state condition.

$$F \cdot Y_i = k_i \cdot V \cdot C_i = (A/W) K_i \cdot V \cdot C_i \qquad (2)$$

$$V \cdot C_i = A \cdot L_f (1-\varepsilon_f) \rho_s \cdot X_i = A \cdot L_{mf} (1-\varepsilon_{mf}) \rho_s \cdot X_i = W \cdot X_i \qquad (3)$$

From Eq.(2) and Eq.(3)

$$K_i = (F \cdot Y_i)(W/A)(V \cdot C_i) = (F/A)(Y_i/X_i) \qquad (4)$$

Ki is calculated by measuring the total weight of elutriated solids per unit time F, and the size distributions of bed and elutriated particles.

3. Experimental Results

Figures 3 and 4, respectively, show the relation between Ki and Ua with $\bar{D}_p$ and De as a parameters in the case where FCC particles and silica sand particles (SM) are fluidized. From Fig.3, when fine particles like FCC particles are fluidized, Ki is not affected by De. However, when the coarse particles are fluidized, Ki increases with decrease of De at the constant gas velocity as shown in Fig.4.

According to Geldart's classification, the particles used in this work are divided into two groups, that is, group A and B. SF, FCC and GF particles belong to group A. SM, SC and GC particles belong to group B. According to Geldart[4] the range of group A is calculated as

$$U_{mf} \leqq 100\ \bar{D}_{p\,32} \qquad (5)$$

Generally, Ki may be affected by Froud number $Fr=(Ua-Uti)/g\,\bar{D}_p$, Reynolds number $Rep=(\rho_g\, Uti\, \bar{D}_p)/\mu$, ρ_s/ρ_g, the minimum fluidized gas velocity and hydraulic diameter of bed De. Figures 5a and 5b, respectively, show the relation between Fr and $Ki/\rho_g(Ua-Uti)$ with De as a parameter in the case where SF particles and SM particles are fluidized. From Fig.5, the power of Froud number is strongly dependent on the particle Reynolds number.

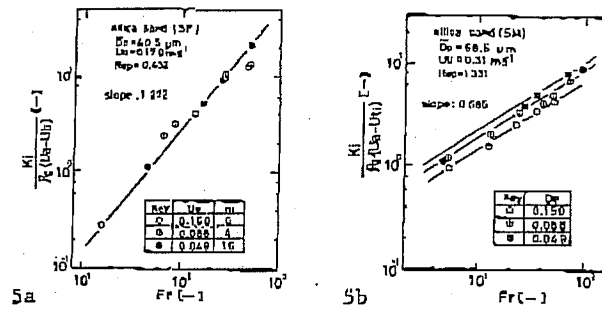


Fig.5 Relation between $Ki/\rho_g(Ua-Uti)$ and Fr

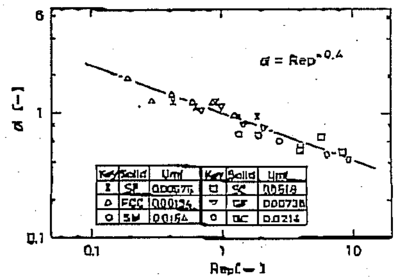
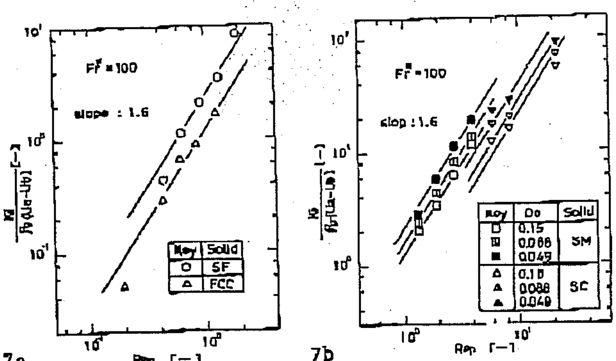


Fig. 6 Relation between the power of Froud number α and Rep.

Figure 6 shows the relation between the power of Froud number α and the particle Reynolds number of i-component particles Rep. The larger the particle Reynolds number is, the smaller α is. α is proportional to $Rep^{-0.4}$.

Figures 7a and 7b show the relation between $Ki/\rho_g(Ua-Uti)$ and Rep at the constant Fr^{α}. From these Figures, $Ki/\rho_g(Ua-Uti)$ is proportional to $Rep^{1.6}$ in all kinds of the particles used in this experiment.

The effect of the hydraulic diameter of the bed on the rate constant is shown in Figure 8. When the fine particles are fluidized, Ki is not affected by De. However, for the coarse particles,



7a 7b

Fig.7 Relation between $Ki/\{\rho_g(Ua-Uti)\}$ and Rep

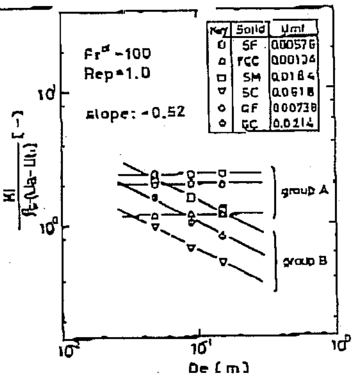


Fig. 8 Effect of De on $Ki/(\rho_g(Ua-Uti))$

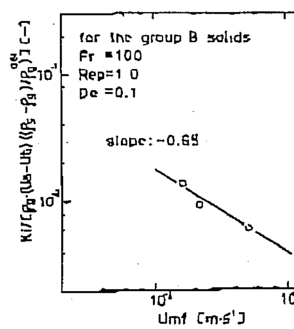


Fig. 9 Effect of Umf

$Ki/\rho_g(Ua-Uti)$ increases with decrease of De and $Ki/\rho_g(Ua-Uti)$ is proportional to $De^{-0.52}$.

The effect of the minimum fluidized velocity Umf on the elutriation rate constant is shown in Figure 9. From this figure the power of Umf is -0.65. Ki was also affected by $(\rho_s-\rho_g)/\rho_g$ and $Ki/\rho_g(Ua-Uti)$ was proportional to $\{(\rho_s-\rho_g)/\rho_g\}^{0.61}$.

The following empirical equations are obtained for the elutriation rate constant Ki from the fluidized bed with and without the vertical multi-tube internals.

For the fine particles like group A of Geldart's classification, Ki is obtained as

$$\frac{Ki}{\rho_g(Ua-Uti)} = 2.07\times10^{-4}\,Fr^{\alpha}\cdot Rep^{1.6}\cdot\left(\frac{\rho_s-\rho_g}{\rho_g}\right)^{0.61} \qquad (6)$$

(when $Umf \leqq 100\,\bar{D}_{p\,32}$), $\alpha = Rep^{-0.4}$

For the coarse particles belonging to the group B of Geldart's classification, Ki is obtained as

$$\frac{Ki}{\rho_g(Ua-Uti)} = 2.65\times10^{-6}\,Fr^{\alpha}\cdot Rep^{1.6}\cdot De^{-0.52}\cdot Umf^{-0.65}\left(\frac{\rho_s-\rho_g}{\rho_g}\right)^{0.61} \qquad (7)$$

(when $Umf > 100\,\bar{D}_{p\,32}$), $\alpha = Rep^{-0.4}$

When the average fluidized particles were small enough, the elutriation rate constant is not affected by Umf. Therefore, Eqs.(6) have not the term of Umf.

Figures 10 and 11, respectively, show the comparison of this experimental data with calculated values from Eqs.(6) and (7). From these figures all experimental data can be correlated by these empirical equations within ±30 % deviation. If De is equal to bed diameter, the elutriation rate constant from an ordinary fluidized bed may be correlated from Eqs.(6) and (7).

The most of the previous investigators used group B particles to measure the rate constant as shown in Figure 1. The experimental values of Ki in the case of small particles were not correlated by their equations. Figure 12 compares the estimated values by equations (6) and (7) with the experimental values of the previous investigators. From Figure 12 other experimental data can be correlated by Eqs.(6) and (7) within ±50 % deviation.

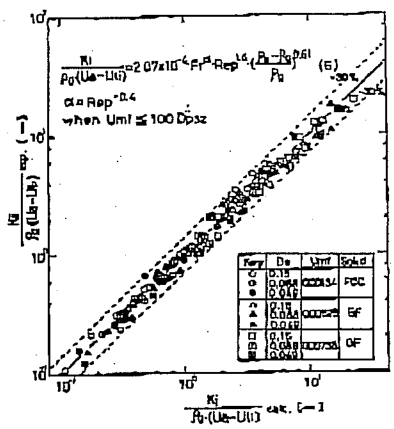


Fig. 10 Comparison of experimental Ki with calculated values from eq.(6) for the group A particles.

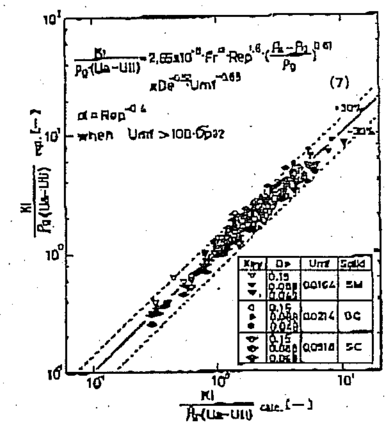


Fig. 11 Comparison of experimental Ki with calculated values from eq.(7) for the group B particles.

4. Conclusion

The elutriation rate constant was measured by gas-solid fluidized bed with and without vertical multi-tube internals. The following results were obtained.

(1) When the size of fluidized particles was fine like group A of Geldart's classification, the elutriation rate constant Ki was not affected by the hydraulic diameter of the tube internals. However, when the group B particles of Geldart's classification were fluidized, the rate constant was affected by the

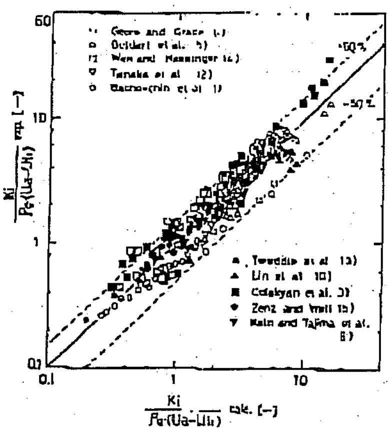


Fig. 12 Comparison of experimental values of other investigators with calculated values by eqs.(6) and (7)

hydraulic diameter De. Generally the rate constant incrcased with decrease of the hydraulic diameter De.

(2) When the average fluidized particles were coarse like group B of Geldart's classification, the elutriation rate constant Ki decreased with increase of the minimum fluidized gas velocity at the constant gas velocity. However, for the fine particles, the rate constant was not affected by the minimum fluidized velocity.

(3) The elutriation rate constant Ki is affected by Froud number, the particle Reynolds number, $(\rho_s-\rho_g)/\rho_g$, Umf and hydraulic diameter De. The empirical equations for the elutriation rate constant from the fluidized bed with and without the vertical multi-tube internals were obtained. The elutriation rate constants from an ordinary fluidized bed obtained by previous investigators were well correlated with the empirical equations.

Nomenclature

A = effective cross sectional area of bed (m^2)
Ci = concentration of i-component particles in bed ($kg\ m^{-3}$)
De = hydraulic diameter of bed (m)
Di = tube diameter of internals (m)
D_p = particle diameter (μm) or (m)
$\bar{D}_p$ = mean particle diameter of i-component particles (μm) or (m)
$\bar{D}_{p32}$ = surface mean diameter of fluidized particles (μm) or (m)
F = total elutriation rate of particles ($kg\ s^{-1}$)
Fr = Froud number defined by $(Ua-Uti)^2/g\,\bar{D}_p$ (-)
g = gravitational accelation ($m\ s^{-2}$)
Ki = elutriation rate constant of i-component particles based on unit cross sectional area ($kg\ m^{-2}\ s^{-1}$)
Lmf = bed height at minimum fluidizing conditions (m)
ni = number of tubes immersed in bed (-)
Rep = particle Reynolds number defined by $\rho_g \cdot Uti \cdot \bar{D}_p/\mu$ (-)
Ua = superficial gas velocity based on A ($m\ s^{-1}$)
Umf = minimum fluidized gas velocity ($m\ s^{-1}$)
Uti = terminal velocity of i-component particles ($m\ s^{-1}$)
V = bed volume at fluidizing conditions (m^3)
W = total weight of bed (kg)
X = cumulative weight fraction of bed particles (-)
Xi = weight fraction of i-component particles in bed (-)
Yi = weight fraction of i-component particles elutriated from the bed (-)
Z = width of column (m)
α = power of Froud number (-)
ϵ_f = voidage at fluidizing conditions (-)
ϵ_{mf} = voidage at the minimum fluidizing conditions (-)
ρ_g = gas density ($kg\ m^{-3}$)
ρ_s = particle density ($kg\ m^{-3}$)
μ = viscosity of gas (Pa-s)

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