APPLICATION OF THE OBSTRUCTION MODEL TO ELUTRIATION OF MORE THAN ONE SPECIES OF PARTICLES FROM MULTICOMPONENT FLUIDIZED BED

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In the previous paper, the authors proposed a simple model which describes elutriations of one particle species from bubbling fluidized beds made up of one- or two-component particles, by consideration of the obstructive effect due to suspended particles in the freeboard. In this report the proposed model was applied to the elutriations of more than one species of particles from multicomponent fluidized beds consisting of glass beads, FCC particles and iron powders. The applicability of the model to such systems and the obtained best-fit values of the model parameters were examined thoroughly. It was proved that the model also describes well the elutriation of more than one species of particles. The virtual elutriation rate constant in the proposed model, which is one of the model parameters and means the imaginary elutriation rate constant without the obstructive effect, agreed well with the conventional elutriation rate constant predicted by the correlation proposed by Wen and Hashinger.

The other parameter k_p was in proportion to the reciprocal of the slip velocity.

1. Introduction

In the elutriation of one particle species from a gas-solid fluidized bed, we found and reported the very interesting phenomenon that the ratio of elutriation rate to particle concentration gradually decreases as particle concentration in the fluidized bed becomes larger. Further, in order to explain the phenomenon, a simple model, in which the existence of an obstructive effect on elutriation due to suspended particles in the freeboard was taken into consideration, was proposed.[2] In the previous study, we also found that the virtual elutriation rate constant, which was imaginary elutriation rate constant when the obstructive effect was assumed not to exist, agreed well with the conventional elutriation rate constant predicted by the equations of Wen and Hashinger and others.[4-7]

In this paper the proposed model is applied to the elutriation of a multicomponent fluidized bed where more than one species of particles fly out of the freeboard simultaneously. The applicability of the model to elutriation of a multicomponent fluidized bed is discussed and two parameters included in the model, the virtual elutriation rate constant a_i and a correction factor k_{pi}, are correlated respectively by the conventional elutriation rate constant and the slip velocity.

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2. Background of Simple Obstruction Model

In the actual freeboard, particles are rising in the core region in the center of the column and falling in the annulus adjacent to the column wall, as reported by Horio *et al.*[1] and Morooka *et al.*[3] The lateral distributions of particle velocity in the axial direction and holdup of solid particles in the core region are almost constant. However, particle velocity and holdup in the core are remarkably different from those in the annulus and both of them change steeply in the limited region around the boundary of the core and the annulus.[3]

The obstruction due to suspended particles in the freeboard introduced in the previous paper[2] is considered to exist mainly in this thin boundary region, because there the collision frequency between rising and falling particles is high. In contrast with the boundary region, it is very difficult for ascending particles to collide with other particles in the inner space of the core, because the direction of motion and velocity of all particles in the core are relatively similar.

If we try to propose a realistic model for the obstruction mechanism, the model has to include many variables such as the area of the region around the boundary of the core and the annulus where collisions between particles take place frequently, the velocities of ascending and descending particles and particle holdups in the core and the annulus, which are extremely difficult for us to determine.

In the previous paper[2] we proposed a simple model, where a portion of the particles entrained from the bed surface is assumed to be prevented from elutriating by the particles suspended homogeneously in the whole space of the freeboard. This simple model includes two parameters, one of which is necessarily prepared to adjust for the deviation from the complicated actual obstruction mechanism. As a matter of fact, small values were obtained for the correction factor k_p, which was prepared for such adjustment in the proposed model,[2] because the obstruction does not occur in the whole of the freeboard but may be concentrated in the limited boundary region between the core and the annulus. Furthermore, not all particles that collide with the suspended particles might return to the bed. As a necessary consequence, k_p depends on the gas velocity and the diameter and density of particles, because these factors influence the particle behavior in the freeboard. For instance, the region where collisions between particles occur frequently might become narrow when the superficial gas velocity becomes high, because the velocity gradient in the boundary region between the core and the annulus then becomes sharp. The number of paritcles retained in the freeboard for a relatively long time might decrease when the size or the density of particles is small, because the apparent ascending velocity of particles becomes high. For these reasons the correction factor, k_p, is expected to relate closely to gas velocity, terminal velocity and slip velocity of particles.

3. Experimental Apparatus and Procedure

Figure 1 is a diagram of the experimental equipment. The fluidized bed, made of steel pipe, was 81 mm in inner diameter and 330 cm in height from the stationary bed surface. The distributor was a perforated plate with 121 holes of 1 mm diameter. The fluidized-bed column has two shutters in the freeboard region and a cyclone at the top for measurement of the amount of holdup particles and of the elutriation rate, respectively. The lower shutter was installed 40 to 100 cm above the bed surface in order to prevent the direct effect of bubble eruption, and the upper shutter was kept at 325 cm in height. The experimental apparatus and procedure are the same as those introduced in the previous paper[2] except for the particles used. For more detail please refer to the previous paper.

Glass beads, FCC particles and iron powders of several sizes each were used as bed particles. Their particulate data are available in **Table 1**. Two, three or four kinds of the particles listed in Table 1 were mixed in arbitrary ratio and used in experimental runs. The total amount of particle mixtures ranged from 1.37 to 4.92 kg. Superficial gas velocities were within 46—100 cm/s and were chosen so as not to exceed the terminal velocity of the largest particle in the bed and not to generate severe slugging.

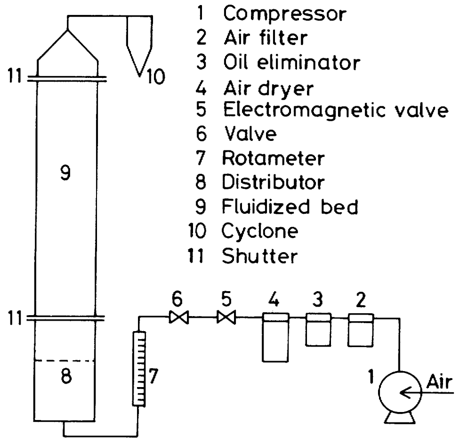

Fig. 1. Schematic diagram of experimental apparatus

Table 1. Particulate data

	Particle size [mesh]	D_p [μm]	U_t [cm/s]
Glass beads (ρ_p = 2520 kg/m^3):			
GCC	60— 80	213.5	348.5
GC	80—100	163.0	128.4
GM	170—200	81.0	50.0
GF	200—250	68.5	35.8
GFF	250—280	58.0	25.7
FCC (ρ_p = 1220 kg/m^3):			
FM	120—145	115.0	48.9
FF	145—170	96.5	34.3
FFF	170—200	81.0	24.2
Iron (ρ_p = 6800 kg/m^3):			
IM	235—280	58.0	69.5
IF	280—330	49.0	49.5

Combinations of particles used and their mass fractions are listed in **Table 2**.

4. Application of Elutriation Model to Multicomponent Fluidized Bed

In general, the elutriation rate constant K^* is defined by Eq. (1), and K^* has been regarded until now as being constant regardless of the mass fraction of particles in a fluidized bed.

$$dWX_{fi}/dt = -V_i = -K_i^* A_t X_{fi} \quad (1)$$

On the contrary, a simple model of the obstructive effect was derived in the previous report for the elutriation of one particle species.[2] In this paper the model is expanded to the elutriation of multicomponent particles. The derivation of the expanded model includes the following assumptions.

Table 2. Combinations of particles and their mass fractions

Run No.	Combination	Mass fraction
Two components		
1	GC-GFF	$X_{fGFF}=0.05, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0$
		$X_{fGC}=1-X_{fGFF}$
2	GC-GF	$X_{fGF}=0.05, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0$
		$X_{fGC}=1-X_{fGF}$
3	GC-GM	$X_{fGM}=0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0$
		$X_{fGC}=1-X_{fGM}$
4	GC-FFF	$X_{fFFF}=0.1, 0.3, 0.5, 0.7, 0.9, 1.0$
		$X_{fGC}=1-X_{fFFF}$
5	GC-FF	$X_{fFF}=0.1, 0.3, 0.5, 0.7, 0.9, 1.0$
		$X_{fGC}=1-X_{fFF}$
6	GCC-IF	$X_{fIF}=0.1, 0.3, 0.5, 0.7, 0.9, 1.0$
		$X_{fGCC}=1-X_{fIF}$
7	GCC-IM	$X_{fIM}=0.1, 0.3, 0.5, 0.7, 0.9, 1.0$
		$X_{fGCC}=1-X_{fIM}$
Three components		
8	GC-GF-GFF	$X_{fGF}=X_{fGFF}=0.025, 0.05, 0.1, 0.2, 0.3, 0.4, 0.5$
		$X_{fGC}=1-X_{fGF}-X_{fGFF}$
9	GC-GF-GFF	$X_{fGF}=0.1, 0.2, 0.3, 0.4, 0.5$
		$X_{fGFF}=0.6-X_{fGF}, X_{fGC}=0.4$
10	GC-GM-GF	$X_{fGM}=X_{fGF}=0.1, 0.2, 0.3, 0.4, 0.5$
		$X_{fGC}=1-X_{fGM}-X_{fGF}$
11	GC-FF-FFF	$X_{fFF}=X_{fFFF}=0.05, 0.15, 0.25, 0.35, 0.45, 0.5$
		$X_{fGC}=1-X_{fFF}-X_{fFFF}$
12	GC-FF-GF	$X_{fFF}=X_{fGF}=0.05, 0.15, 0.25, 0.35, 0.45, 0.5$
		$X_{fGC}=1-X_{fFF}-X_{fGF}$
13	GCC-IM-IF	$X_{fIM}=X_{fIF}=0.05, 0.15, 0.25, 0.35, 0.45, 0.5$
		$X_{fGCC}=1-X_{fIM}-X_{fIF}$
Four components		
14	GC-GM-GF-GFF	$X_{fGM}=X_{fGF}=X_{fGFF}=0.05, 0.1, 0.15, 0.27, 0.33$
		$X_{fGC}=1-X_{fGM}-X_{fGF}-X_{fGFF}$
15	GC-FM-FF-FFF	$X_{fFM}=X_{fFF}=X_{fFFF}=0.05, 0.1, 0.15, 0.27, 0.33$
		$X_{fGC}=1-X_{fFM}-X_{fFF}-X_{fFFF}$

Assumptions

(1) When more than one species of particles are entrained from the bed surface, the elutriation rate of each species at the bed surface is in proportion to both the cross-sectional area of the fluidized bed and its own mass fraction. This means that the existence of other particle species in the dense bed does not affect the entrainment rate of particular particle species at the bed surface.

(2) Particles entrained from the bed surface are rejected to the dense bed if they collide with the suspended particles in the freeboard.

(3) The particles that exist in the freeboard are suspended homogeneously and remain still regardless of particle size or material.

On the basis of assumptions (2) and (3), all suspended particles in the freeboard are considered to act as a filter for each kind of ascending particles. The obstruction efficiency of each particle, E_i, is expressed in the form of the logarithmic-penetration law.

$$E_i = 1 - \exp\left\{-\frac{3L(1-\varepsilon)(D_{fs}+D_{pi})^2}{2D_{fv}^{\ 3}}\right\} \tag{2}$$

where ε is voidage in the freeboard. Mean surface and mean volume diameters of particles suspended in the freeboard are taken as D_{fs} and D_{fv} respectively. D_{pi} is the diameter of an ascending particle.

The virtual elutriation rate of each particle can be regarded as in proportion to the cross-sectional area of the fluidized bed and its mass fraction from assumption (1).

$$V_i' = a_i A_t X_{fi} \tag{3}$$

Consequently, we can obtain Eq. (4) for the apparent elutriation rate of i-th particle species.

$$\begin{aligned} V_i &= V_i'(1-E) \\ &= a_i A_t X_{fi} \exp\left\{-\frac{3k_{pi}L(1-\varepsilon)(D_{fs}+D_{pi})^2}{2D_{fv}^{\ 3}}\right\} \end{aligned} \tag{4}$$

where a_i is the elutriation rate constant of i-th particle species when the obstructive effect does not exist. In other words, it is the rate constant corresponding to the "virtual elutriation rate". A correction factor k_{pi} is introduced in the exponential term of Eq. (4) to account for the error introduced by the assumptions. Equation (4) has two parameters, a_i and k_{pi}, whose values are determined by fitting experimental data of the elutriation rate and the concentration of particles suspended in the freeboard.

5. Experimental Results and Discussion

As an example, **Figs. 2** and **3** show the effect of mass fractions of entrained particles on the elutriation rate constant, K_i^*, determined for a three-component fluidized bed. In this example, GF and GFF-particles were elutriated from the fluidized bed column. The results were obtained when mass fractions of GF-particles, X_{fGF}, and GFF-particles, X_{fGFF}, were arranged to be equal to each other.

The experimental values of K_i^* indicated by circles in Figs. 2 and 3 were directly determined by Eq. (1) from the measured elutriation rates. They strongly depend on mass fractions of both GF-particles and GFF-particles in Figs. 2 and 3. This result of the tertiary system is very similar to the previously reported experimental results[2)] in binary fluidized beds where only one component was elutriated. This shows that the obstructive effect exists clearly even in the elutriation of a multicomponent fluidized bed where more than one species of particles are elu-

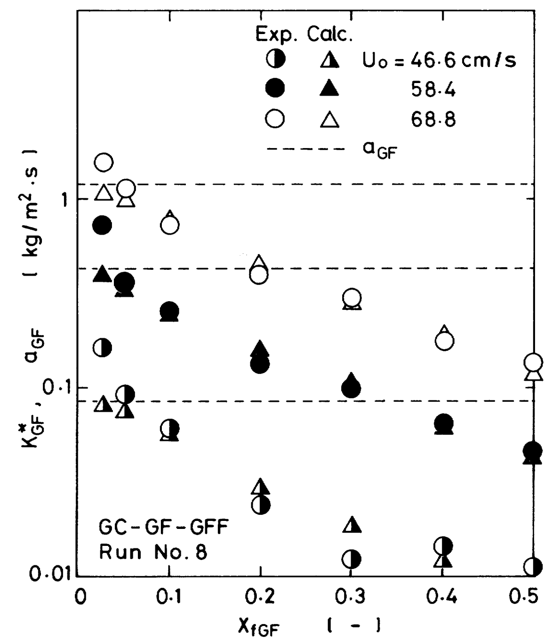

Fig. 2. Effect of X_{fGF} on elutriation rate constant of GF-particle

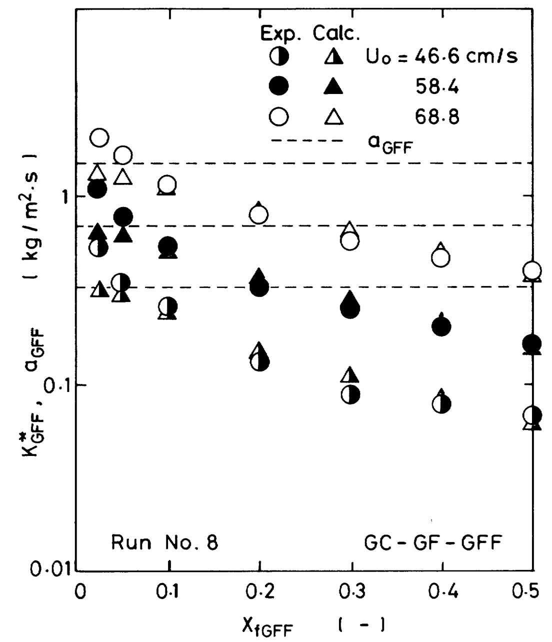

Fig. 3. Effect of X_{fGFF} on elutriation rate constant of GFF-particle

triated.

Next, we applied Eq. (4) to the experimental data and obtained the best-fit values of parameters a_i and k_{pi}. The values of K_i^* indicated by triangles in the figures were calculated by substituting elutriation rates, predicted by Eq. (4) with best-fit values of a_i and k_{pi}, into Eq. (1). Comparison between circles and triangles in Figs. 2 and 3 shows the good applicability of the model to the present experimental results. This result makes it clear that the proposed model is applicable to elutriation from a tertiary

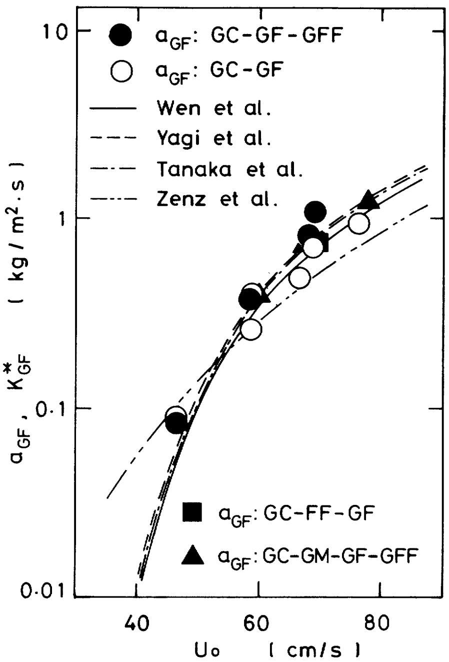

Fig. 4. Effect of U_0 on a and K^* predicted by previous correlations

system as well as from the binary fluidized beds introduced in the previous paper.[2)]

Figure 4 shows the best-fit values of a_i for GF-particles, determined by parameter fitting for two- to four-component systems. The curved lines in Fig. 4 also show the elutriation rate constants predicted by the correlations derived by Wen and Hashinger,[5)] Yagi and Aochi,[6)] Tanaka *et al.*[4)] and Zenz and Weil.[7)]

All equations used here are listed below, as Eqs. (5) to (8).

Wen and Hashinger:

$$\frac{K^*}{\rho_g(U_0-U_t)}=1.52\times10^{-5}\left\{\frac{(U_0-U_t)^2}{gD_p}\right\}^{0.5}Re^{0.725}\times\left(\frac{\rho_p-\rho_g}{\rho_g}\right)^{1.15}\left(\frac{U_0-U_t}{U_t}\right)^{0.1} \quad (5)$$

Yagi and Aochi:

$$\frac{K^*gD_p^{\,2}}{\mu(U_0-U_t)^2}=0.0015Re^{0.6}+0.01Re^{1.2} \quad (6)$$

Tanaka *et al.*:

$$\frac{K^*}{\rho_g(U_0-U_t)}=4.6\times10^{-2}\left\{\frac{(U_0-U_t)^2}{gD_p}\right\}^{0.5}Re^{0.3}\times\left(\frac{\rho_p-\rho_g}{\rho_g}\right)^{0.15} \quad (7)$$

Zenz and Weil:

$$\frac{K^*}{\rho_g U_0}=[(U_0/\sqrt{gD_p})(81.4/\rho_p)]^3 \quad (8)$$

The good agreement of a_i and calculated K_i^* shows that the virtual elutriation rate, V_i', defined by Eq. (3), can be determined by some published correlations with high accuracy under the assumption that the no obstructive effect exists. Furthermore, four correlations between a_i and U_0 for each system shown in Fig. 4 are similar to each other regardless of the number or combination of particle species in the fluidized-bed system.

Figure 5 shows a comparison between the virtual elutriation rate constant, a_i, obtained by parameter fitting and the elutriation rate constant predicted by the correlation derived by Wen and Hashinger[5] as an example of the conventional ones. Regardless of the number of components or particle material, the virtual elutriation rate constants agree well with K_i^* values predicted by Wen and Hashinger.

Figure 6 shows the relationship of the other parameter k_{pi} to superficial gas velocity for the elutriation of glass beads from two- to four-component fluidized beds. k_{pi} decreased significantly as the superficial gas velocity, U_0, became higher. However, the effect of particle size was not so large and k_{pi} dropped slightly with decrease in particle diameter. We can find that k_{pi} is almost independent of the combination and number of glass beads in the fluidized bed when the particle size and U_0 are fixed.

We rewrote the data in Fig. 6 by taking the slip velocity as the abscissa in order to try to treat the effects of particle size, particle density and gas velocity inclusively. An adequate correlation between k_{pi} and $U_0 - U_t$ is found in **Fig. 7** except for some experimental data, such as FCC particle of a four-component system. k_{pi} is almost in proportion to the reciprocal of the slip velocity even though the simple model is being applied to the complicated obstructive phenomenon in the freeboard.

It is required to verify if this relationship between k_{pi} and slip velocity is valid for any experimental condition other than those examined here. It is also necessary to make clearer the movement and collision of particles in the freeboard and to clarify the detailed obstruction mechanism which supports the relationship introduced here.

Conclusion

(1) As X_f became larger, the elutriation rate constant, K^*, decreased in the same manner as K^* in the fluidized bed where only one particle species was elutriated.

(2) A simple elutriation model, which was derived in consideration of the obstructive effect due to suspended particles in freeboard, was applied to the elutriations of more than one species of particles from multicomponent fluidized beds.

(3) The virtual elutriation rate constant, a, which

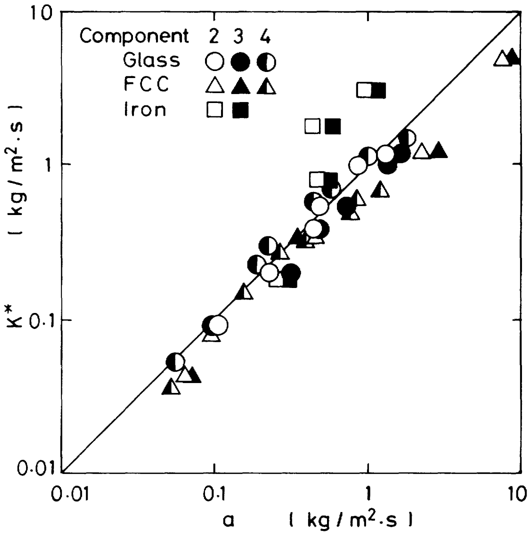

Fig. 5. Comparison between a obtained from Eq. (4) and K^* predicted by Eq. (5)

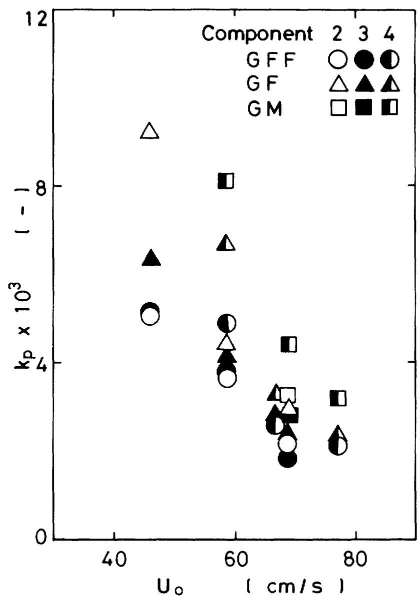

Fig. 6. Effect of superficial gas velocity on k_p

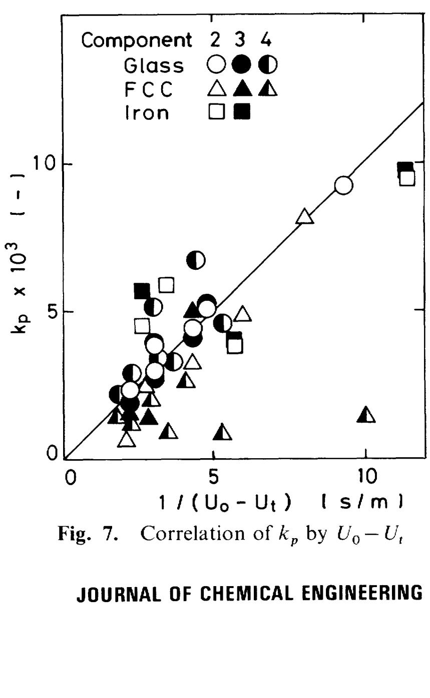

Fig. 7. Correlation of k_p by $U_0 - U_t$

is one of the model parameters, can be predicted well by the correlations of the conventional elutriation rate constant proposed previously, for example, by Wen *et al.* It also agreed with a obtained for the elutriation of the same particle species where only one species was elutriated.

(4) The other parameter, k_p, also agreed with that obtained for the elutriation of the same particle species where only one species was elutriated.

(5) Dependencies of k_p on particle diameter and density and superficial gas velocity were generalized in terms of $U_0 - U_t$. k_p is almost in proportion to the reciprocal of the slip velocity.

Nomenclature

A_t	= cross-sectional area of fluidized bed	[m^2]
a	= virtual elutriation rate constant in Eq. (4)	[kg/m^{2}s]
C	= mean holdup in freeboard	[kg/m^3]
D_{fs}	= mean surface diameter of particles suspended in freeboard	[m]
D_{fv}	= mean volume diameter of particles suspended in freeboard	[m]
D_p	= diameter of elutriated particle	[m]
E	= obstruction efficiency	[—]
g	= acceleration of gravity	[m/s^2]
K^*	= elutriation rate constant	[kg/m^{2}s]
k_p	= correction factor in Eq. (4)	[—]
L	= length of freeboard	[m]
Re	= $U_t \rho_g D_p / \mu$	[—]
U_0	= superficial gas velocity	[m/s]
U_t	= terminal velocity of particle	[m/s]
V	= elutriation rate	[kg/s]
V'	= virtual elutriation rate without obstructive effect	[kg/s]
W	= weight of fluidized bed	[kg]
X_f	= mass fraction of particle	[—]
ε	= voidage of freeboard	[—]
μ	= viscosity of gas	[kg/m·s]
ρ_g	= density of gas	[kg/m^3]
ρ_p	= density of particle	[kg/m^3]

⟨Subscript⟩

i	= i-th component of particle

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