OBSTRUCTIVE EFFECT ON ELUTRIATION DUE TO EXISTENCE OF PARTICLES IN FREEBOARD

HIROYUKI KAGE, MANABU TSUMORI AND YOSHIZO MATSUNO
Department of Applied Chemistry, Kyushu Institute of Technology, Kitakyushu 804

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In many previous investigations, the elutriation rate of multi component gas-solid fluidized beds has been reported to be in proportion to the concentration of particles in the bed. We, however, found the very interesting phenomenon that the ratio of elutriation rate to particle concentration gradually decreases as the concentration becomes larger. A simple model, in which the obstructive effect on elutriation due to suspended particles in the freeboard is taken into consideration, is proposed and applied to elutriation from a fluidized bed which consisting of two kinds of glass beads of different sizes. The virtual elutriation rate in the proposed model, which is the imaginary elutriation rate when no obstructive effect exists, agrees well with the common elutriation rate predicted by the equations proposed previously, such as that by Wen and Hashinger. The other parameter in the model, k_p, which relates directly to the magnitude of the obstructive effect, decreases as the superficial gas velocity becomes high.

Introduction

Many investigators have proposed correlating equations for the elutriation rate of solid-gas fluidized beds.[3-5,8,10-13] In general, it has been thought that the particle elutriation rates from a solid-gas fluidized bed are in proportion to the particle concentrations in the bed. An exception is the report by Geldart *et al.*[2] They reported that the existence of alumina particles remarkably promotes the elutriation of sand from a fluidized bed consisting of a mixture of sand and alumina particles. In contrast to this traditional way of thinking, we observed in our experiments that the ratio of elutriation rate to particle concentration gradually decreases as the concentration becomes larger. We propose a simple model in which the obstructive effect on elutriation owing to the existence of particles in the freeboard is taken into consideration, and investigate the relationship between the elutriation rate and the amount of suspended particles in the freeboard.

1. Experimental Apparatus and Procedure

A schematic diagram of the experimental apparatus is illustrated in **Fig. 1**. The fluidized bed, made of steel pipe, is 81 mm in I.D. Its distributor is a perforated plate with 121 holes (1 mm diameter) and 6.5 mm rectangular pitch. The freeboard height is 330 cm from the stationary bed surface, and a cyclone for the collection of elutriated particles is installed at the top of the fluidized-bed column. The column has two shutters in the freeboard region for measurement of the amount of holdup particles. The lower shutter is installed 40 or 60 cm above the bed surface in order to prevent the direct effect of bubble eruption, while the upper shutter is 325 cm above the bed surface in the usual case.

Four kinds of glass beads of 2520 kg/m^3 in density are used as bed particles. Their average diameters are 163, 81, 68.5 and 58 μm, and we denote them C, M, F, and FF-particle, respectively. Two kinds of glass beads (C-M, C-F, C-FF) are mixed in arbitrary ratio and placed in the column to make up a two-component fluidized bed. The total content of glass beads is always kept at 2.0 kg. Air at room temperature is used as fluidizing gas. Eight superficial gas velocities, 46.6,

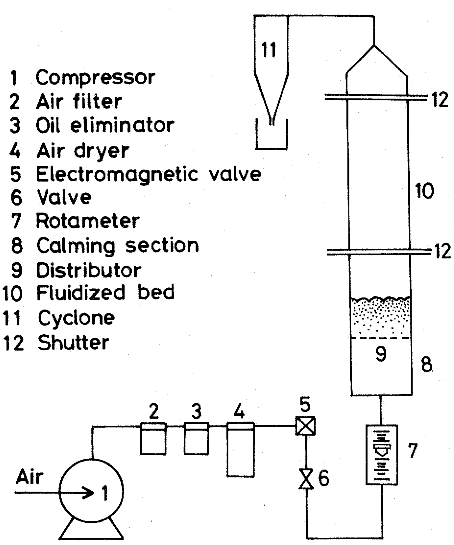

Fig. 1. Schematic diagram of experimental apparatus

* Received July 23, 1990. Correspondence concerning this article should be addressed to H. Kage. M. Tsumori is now with Sumitomo Seika Chemicals Co., Ltd., Osaka 541.

50.7, 58.4, 66.7, 68.8, 76.3, 87.0 and 99.6 cm/s, are chosen so as not to exceed the terminal velocity of C-particle and not to generate severe slugging.

The elutriated particles are collected by the cyclone, and then the elutriation rate constant is determined from the weight of the particles collected per unit time. The mass of the suspended particles between the two shutters is also measured, and its quotient divided by the freeboard volume between the two shutters gives the mean particle holdup in the freeboard. Batch operation is used in this study, but it was confirmed that the amount of particles flowing away from the fluidized bed until the end of each experimental run is too small to influence the total content or the composition of the bed particles.

The particulate data are summarized in **Table 1**.

Table 1. Particulate data

	C	M	F	FF
Particle size [mesh]	80–100	170–200	200–250	250–280
Mean diameter [μm]	163.0	81.0	68.5	58.0
Terminal velocity [cm/s]	128.4	50.0	35.8	25.7

2. Obstructive Effect on Elutriation by Suspended Particles

Figure 2 shows an example of the relationship between the mass fraction of finer particle in fluidized bed, X_f, and its elutriation rate, V. In this figure, C-F two-component system is introduced and X_f and V represent respectively the mass fraction and elutriation rate of F-particle. The gas velocity is adjusted so as to entrain only F-particle. The elutriation rate shown in Fig. 2 is not in proportion to X_f, and the increment of V becomes lower in the high-X_f region.

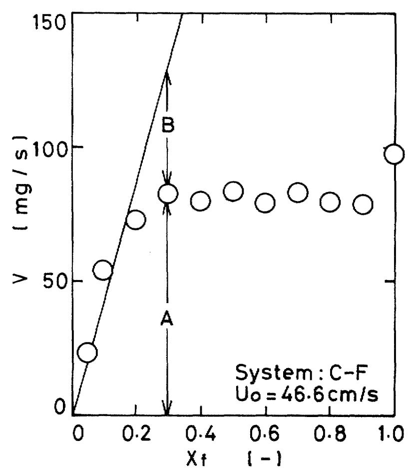

Fig. 2. Effects of X_f on elutriation rate

The concept of the elutriation rate constant has spread broadly, and many investigators have used it. However, some versions of its definition have been introduced[5,10,11] because of confusion in the numerical formula. One of them is Eq. (1) by Wen and Hashinger.[11]

$$dX_f/dt = -KA_tX_f/W \tag{1}$$

Horio *et al.*[3] pointed out this confusion and recommended Eq. (2) as a new definition of the elutriation rate constant.

$$dWX_f/dt = -V = -K^*A_tX_f \tag{2}$$

In **Fig. 3**, where the data of Wen and Hasinger[11] are plotted, they also showed that the elutriation rate constant becomes independent of X_f when defined by Eq. (2). Since then it has been commonly thought that the elutriation rate is in proportion to the mass fraction. If the elutriation phenomenon in the present study also obeys Eq. (2), the elutriation rate has to increase along the straight line in Fig. 2.

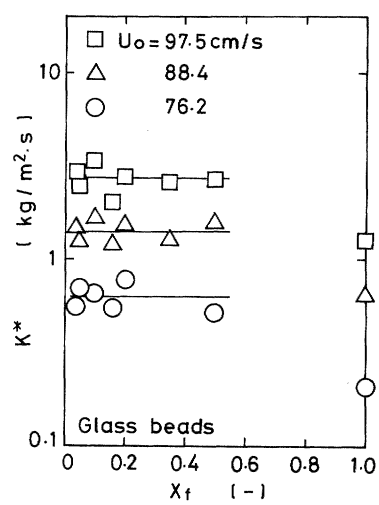

Fig. 3. Elutiration rate constant for experimental data reported by Wen and Hashinger

Such an elutriation rate that is not proportional to X_f was reported by Sycheva and Donat[9] for a mixture of aluminosilicate catalysts. Bachovchin *et al.*[1] also found that the elutriation rate from sand mixture was not in proportion to its concentration and surmised that it was owing to a blockage of interstitial gas flow channels by fine sand or a lower fines concentration at the bed surface. However, unequivocal explanations of these two reports have not yet been obtained.

Figure 4 shows the relationship between X_f and the mean holdup in the freeboard for the same system as Fig. 2. The holdup of finer particle increases smoothly and almost linearly as the mass fraction becomes larger. Its features are in contrast to the relationship of V and X_f in Fig. 2.

As X_f increases, the holdup increases smoothly, while the elutriation rate does not obey Eq. (2). This discrepancy can be explained by the obstructive effect

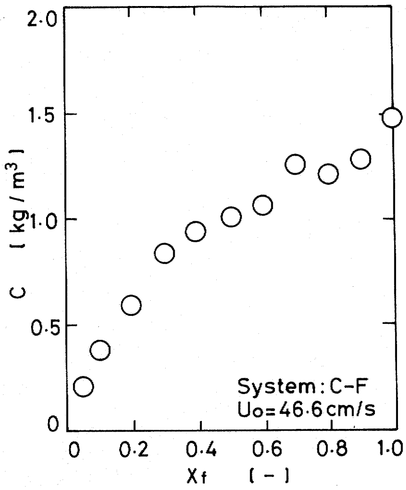

Fig. 4. Effect of X_f on holdup in freeboard

of the holdup particles suspended in the freeboard. Essentially, the elutriation rate at the bed surface ought to be in proportion to X_f and to agree with the straight line in Fig. 2. A part of the entrained particles, however, collides with the suspended particles in the freeboard during the former's ascent and, prevented from elutriation, returns to the bed. The obstructive effect becomes more remarkable when X_f becomes larger, because the holdup increases. The elutriation rate approaches the straight line in Fig. 2 when the obstructive effect is very small and can be neglected. This line is regarded as the "virtual elutriation rate," which is the imaginary elutriation rate when no obstructive effect exists. A in Fig. 2 shows the particles apparently elutriated and B shows the particles obstructed by the suspended particles in the freeboard. The "obstruction efficiency," E, can be described by Eq. (3).

$$E = B/(A+B) \tag{3}$$

3. Simple Model of the Obstructive Effect

A simple model of the obstructive effect on the elutriation is derived on the basis of the following assumptions.

Assumptions

(1) The particles that exist in the freeboard are suspended homogeneously and stay still.

(2) All entrained particles that collide with the suspended particles in the freeboard return to the dense bed.

In this model, the suspended particles in the freeboard are considered to act as a filter for the ascending particles. **Figure 5** shows the outline of the model. In the freeboard of length L, we consider n stages of serial filter layers with thickness L/n. Because the number of suspended particles in the first filter layer (shaded region in Fig. 5) is $(L/n)(1-\varepsilon)/(4/3)\pi(D_p/2)^3$, the probability of collision of the ascending particles can be described by Eq. (4).

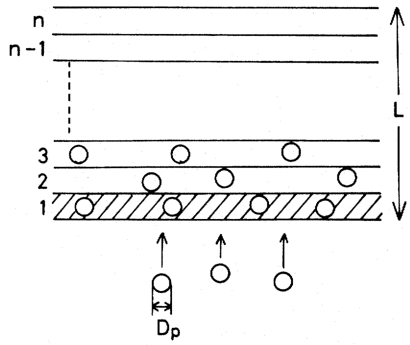

Fig. 5. Obstructive mechanism to ascending particles by suspended particles

$$E_1 = \frac{(L/n)\cdot(1-\varepsilon)}{(4/3)\cdot\pi\cdot(D_p/2)^3}\pi\cdot D_p^2 \tag{4}$$

So the probability of collision of the entrained particles in the freeboard of length L is obtained as Eq. (5).

$$E_n = 1-(1-E_1)^n \tag{5}$$

When we take the limit as n becomes infinite, the obstruction efficiency is expressed in the form of the log-penetration law.

$$E = 1-\exp\{-6L(1-\varepsilon)/D_p\} \tag{6}$$

E in Eq. (6) corresponds to the obstruction efficiency of Eq. (3). Strictly speaking, however, the assumptions used for the derivation of Eq. (6) do not hold true. In the actual freeboard, particles are ascending in the central core and descending in the annulus adjacent to the column wall, as reported by Horio *et al.*[4] and Morooka *et al.*[6] Therefore, the obstruction does not occur through all the space in the freeboard, but occurs mainly in the limited boundary region between core and annulus where the frequency of collision between ascending and descending particles is relatively high. Further, not all particles that collide with the suspended particles may return to the bed in practice. To account for the errors introduced by the assumptions, the power of the exponential in Eq. (6) is multiplied by the correction factor, k_p. Therefore, k_p seems to be closely related to the flow conditions of gas and solids.

The virtual elutriation rate can be regarded as in proportion to the cross-sectional area of fluidized bed and the mass fraction of particle.

$$V' = aA_tX_f \tag{7}$$

where a is a constant of proportionality and corresponds to the elutriation rate constant when no obstructive effect exists. Finally we can obtain the following equation for the apparent elutriation rate.

$$V = V'(1-E) = aA_tX_f\exp\{-6k_pL(1-\varepsilon)/D_p\} \tag{8}$$

Equation (8) has two adjustable parameters, a and k_p, which are determined from experimental results.

To derive a more strict model, we must take the more detailed behavior of solids into consideration. For example, the annular particle flow model by Nakamura and Capes[7] may be used for this purpose. Such a strict model describes the phenomenon more faithfully, but it must include many variables such as particle velocity and holdup in both annulus and core regions. The existence of many variables induces great difficulties in experimental measurement; otherwise it increases the number of unknown parameters in the model. The simple model can describe the obstructive effect sufficiently for the present study.

4. Experimental Results and Discussion

Figure 6 shows the effect of mass fraction on the elutriation rate constant, K^*. K^* as directly calculated by Eq. (2) from the measured elutriation rate (circles) strongly depends on the mass fraction. This feature disagrees with previous reports on the elutriation,[3,10-12] and suggests the existence of the obstructive effect. We applied the proposed simple model to the experimental results and searched the optimal values of the parameters, a and k_p, in Eq. (8) by the parameter-fitting method. The triangle keys in Fig. 6 show K^* values which are calculated from Eqs. (2) and (8) by use of the obtained optimal values of a and k_p and holdups measured by experiment. The good agreement of the calculations with the experimental results shows that the obstructive effect is described sufficiently well by the proposed model. The broken lines in Fig. 6 show the parameters, a, which mean the virtual elutriation rate constant without the obstructive effect, and the difference between broken lines and plotted keys corresponds to the obstructive effect. Similar results were observed in all other combinations of glass beads attempted in this study.

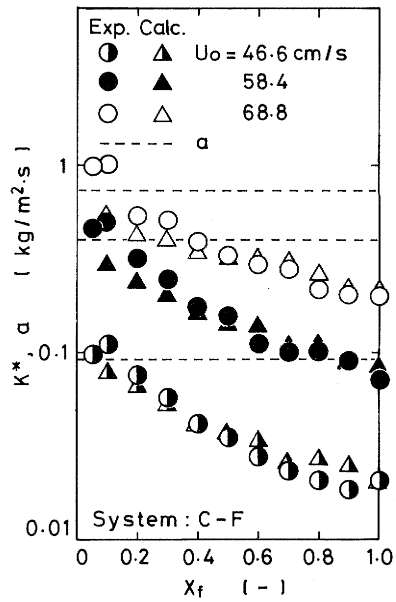

Fig. 6. Effect of X_f on elutriation rate constant

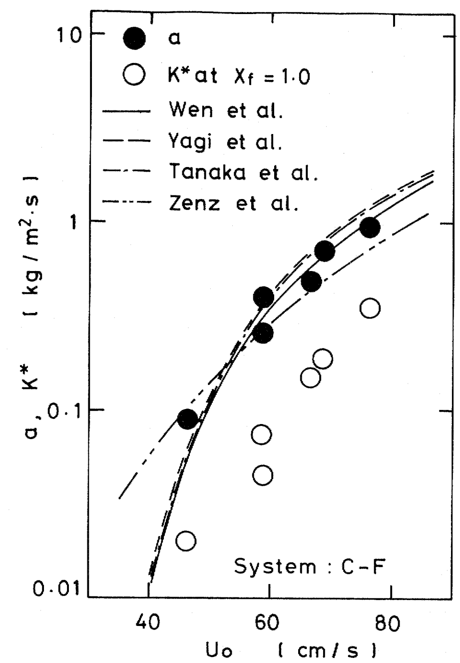

Fig. 7. Comparison between a and K^* predicted by some correlation equations

In **Fig. 7**, K^* at $X_f = 1.0$ and the virtual elutriation rate constant, a, are plotted against the superficial gas velocity. The difference between a and K^* at each value of U_0 shows the magnitude of the obstructive effect. Both K^* and a become larger as the superficial velocity increases. The curved line in Fig. 7 shows the elutriation rate constants predicted by the correlation equations derived by Wen and Hashinger,[11] Yagi and Aochi,[12] Tanaka *et al.*[10] and Zenz and Weil.[13] The predictions agree well with a, and it shows that the elutriation rate can be predicted by some correlation equations with high accuracy when no obstructive effect exists.

The experimental data of Wen and Hashinger,[11] which are the base of the derivation of their correlation equation, are shown in Fig. 3. The experimental data of Wen and Hashinger were mainly measured in the region below $X_f = 0.2$. In particular, there were no data except at $X_f = 1$ for the mass fraction above 0.5, where the obstructive effect may not be so small. Further, their data were measured under the condition of shorter freeboard length and lower superficial gas velocity than in our experiments. We guess that the obstructive effect was relatively small under such experimental conditions and that it was difficult to find out the obstructive effect in their study. In Fig. 3, however, K^* at $X_f = 1.0$, which means one component, is much lower than K^* in the low-X_f region. This suggests the possibility of the obstructive effect at $X_f = 1.0$ even in the experiments by Wen *et al.*

Until now few detailed studies have been reported for the comparison between the elutriation rate constant from a one-component fluidized bed ($X_f = 1.0$) and from a two-component fluidized bed which consists of the same particle as the one-component bed and one more particle too large to be elutriated. According to Fig. 6, however, we find that the elutriation from a one-component fluidized bed is nothing but a special case of the two-component bed, and that the values of a are the same if the obstructive effect is taken into consideration.

Figure 8 shows the value of parameter k_p. We can find that k_p decreases significantly and thus the obstructive effect also becomes small as the superficial gas velocity becomes higher. When the gas velocity is low, the residence time of the entrained particles in the freeboard becomes relatively long. Consequently, the collision between particles and the resultant value of k_p increase, because the distance moved in the radial direction of the particles may become relatively large. The value of k_p falls slightly with decreasing particle diameter, but the effect of particle size is small.

5. Application of the Model to Part of the Freeboard

Up to now, the whole freeboard has been regarded as one body and the averaged holdup data independent of the freeboard height are used for the determination of the parameter k_p. However, k_p, which is closely related to the gas and solid flow conditions in the freeboard, is not yet confirmed to be independent of the freeboard height. Further, it is very difficult to verify whether the real elutriation rate of the particles just at the bed surface, where the obstructive effect does not yet exist, agrees well with V' or aA_tX_f because of the existence of bubble eruption and slugging in the space near the bed surface. Therefore, as shown in **Fig. 9**, we divided the freeboard into three parts ($z = 0$–150, 150–230, 230–330 cm) and examined the reliability of the model by applying it to the upper two parts of the freeboard.

The experimental procedure is as follows. First the elutriation rate is measured by setting a cyclone at z_1. Next, the position of the cyclone is moved to z_2 and shutters are installed at z_1 and z_2. The holdup between z_1 to z_2 and the elutriation rate at z_2 are measured under the same experimental conditions. The model is applied to the freeboard of z_1 to z_2 by regarding the elutriation rate measured at z_1 as V', and the local value of parameter k_p, k_{pl}, at $z = 190$ cm ($= (z_1 + z_2)/2$) is evaluated from the holdup and the elutriation rate obtained at z_2. Similar experiments and calculations are also made for the freeboard of $z = 230$ to 330 cm.

The determined values of k_{pl} are shown in **Fig. 10**. The horizontal lines represent k_p obtained when the freeboard of 330 cm height is treated as one body.

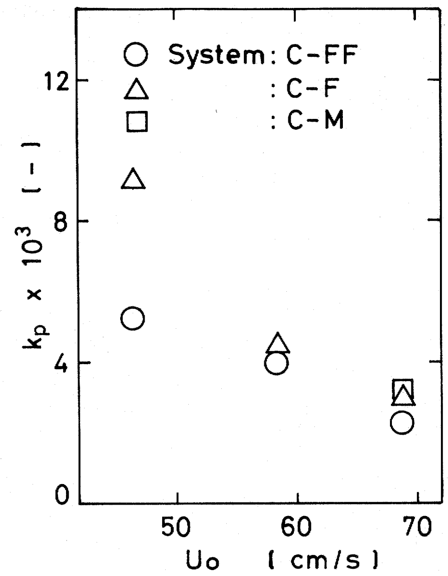

Fig. 8. Effect of superficial gas velocity on k_p

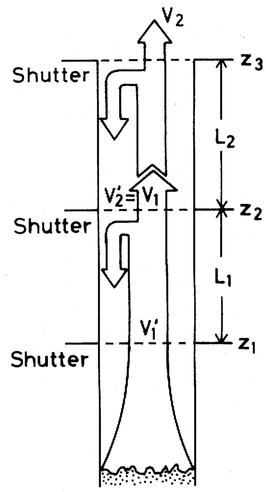

Fig. 9. Application of model to part of freeboard

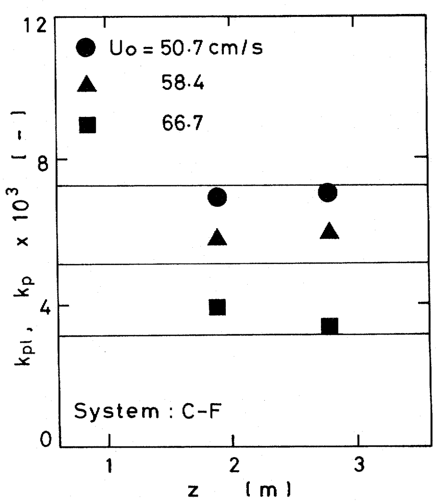

Fig. 10. Comparison of k_{pl} with k_p

Figure 10 shows that k_{pl} values are almost independent of height and agree well with k_p.

These results suggest that V', that is, aA_tX_f, corresponds to the real elutriation rate at the fluidized bed surface when the whole freeboard is regarded as one body, and verify the reliability of the proposed simple model.

Conclusions

(1) The elutriation rate constant, K^*, is not independent of X_f, but decreases as X_f becomes large.

(2) Considering the obstructive effect due to suspended particles in the freeboard, a simple elutriation model is proposed.

(3) One adjustable parameter, a, in the proposed model, which means the virtual elutriation rate constant, can be evaluated by the equations proposed previously, for example, by Wen and Hashinger.

(4) The other parameter, k_p, decreases significantly as the superficial gas velocity becomes higher. However, it falls slightly with decreasing particle size.

(5) The fact that the local values of k_p, k_{pl}, which are determined by applying the model to one portion of the freeboard agree well with k_p proves the reliability of the model.

Nomenclature

A	= mass of particles elutriated from top of freeboard	[kg/s]
A_t	= cross-sectional area of fluidized bed	[m^2]
a	= parameter in Eq. (8)	[kg/m^2 s]
B	= mass of particles which return to fluidized bed	[kg/s]
C	= mean holdup in freeboard	[kg/m^3]
D_p	= particle diameter	[m]
E	= obstruction efficiency	[—]
E_1	= collection efficiency in first filter layer	[—]
E_n	= collection efficiency in n stages of filter layer	[—]
K	= elutriation rate constant in Eq. (1)	[kg/m^2 s]
K^*	= elutriation rate constant in Eq. (2)	[kg/m^2 s]
k_p	= parameter in Eq. (8)	[—]
k_{pl}	= local value of k_p	[—]
L	= length of freeboard	[m]
n	= number of stages	[—]
t	= time	[s]
U_0	= superficial gas velocity	[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 finer particle	[—]
z	= height from surface of dense fluidized bed	[m]
ε	= voidage of freeboard	[—]

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