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The Effect of Swirling Flow on Elutriation in a Vortexing Fluidized Bed

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Abstract–The elutriation of fine particles in a vortexing fluidized bed (VFB) was studied by a batch and binary system. The diameter of the coarse particles was 545 μm, and the diameter of the fine particles for the elutriation test was 81, 97, 115, 137, 163, and 193 μm, respectively. It was found that the swirling flow caused by the secondary air injection is the dominating factor to influence the elutriation rates. The effect of primary air velocity, swirling flow, injection angle of secondary air nozzle, and diameter of fine particles on the elutriation rate constant was also studied. The Taguchi experimental method and Regular analysis are used to identify the effects of various operating variables. A correlation was developed to estimate the specific elutriation rate constant (K^*_∞) in the vortexing fluidized bed. The specific elutriation rate constant (K^*_∞) was found to be a function of the primary air velocity, the diameter of fine particles, the secondary air velocity, and the height of secondary air injection.

Key words : Vortexing Fluidized Bed (VFB), Elutriation, Swirling Flow, Taguchi Experimental Method, Regular Analysis

INTRODUCTION

The elutriation of fine particles from a fluidized bed is a very important topic in the application of fluidized bed techniques. For fluidized bed combustion, the excessive amounts of fly ash and unburned carbon elutriated from a combustor cause poor combustion efficiency and air pollution. In order to increase the residence time of fine particles in the freeboard and prevent fine particles elutriation from the bubbling fluidized bed combustor (BFBC), Korenberg [1984] integrated a combustor and a cyclone. Based on Korenberg's [1984] conception, the Vortexing Fluidized Bed Combustor (VFBC) was developed and named by Nieh and Yang [1987]. The performance of a VFBC can be characterized by the swirling gas flow rate in the freeboard, which is the dominant factor for particle elutriation and combustion efficiency.

Usually, the specific elutriation rate constant (K^*_∞) is affected significantly by the slip velocity, (U_o-U_t), the difference between the superficial gas velocity and the particle terminal velocity. The slip velocity, which is believed to be the most important determining factor for particle hold-up in the freeboard, plays an important role in the mechanism of elutriation [Colakyan and Levenspiel, 1984; Kage et al., 1992; Nakagawa et al., 1994].

The value of the specific elutriation rate constant (K^*_∞) obtained in VFB decreased more significantly than that without secondary air injection [Wan and Chyang, 1998]. Because of the swirling flow caused by the secondary air tangentially injected into the freeboard in the VFB, entrained particles in the freeboard hit the column wall and then fall back into the bed. Therefore, the elutriation rate of the VFB decreases significantly over that of a conventional BFB [Chyang et al., 1996].

In this study, the effects of swirling flow, primary air velocity (U_1), injection angle of secondary air (β^o), and the diameter of fine particles on the specific elutriation rate constant (K^*_∞) were determined. The Taguchi experimental method and Regular analysis were used to identify the effects of various operating variables on the elutriation rate. Finally, a correlation of the specific elutriation rate constant (K^*_∞) was submitted to estimate the elutriation rate. The specific elutriation rate constant (K^*_∞) was found to be a function of the primary air velocity, the diameter of fine particle, the secondary air velocity, and the height of secondary air injection.

EXPERIMENTAL

A schematic diagram of the experimental apparatus is shown in Fig. 1. The vortexing fluidized bed column was fabricated with transparent acrylic column of 0.19 m I.D and 4.0 m height. A 9.0 mm thick perforated plate drilled with 2 mm hole and 2.28% open area ratio was used as a gas distributor.

Glass beads were used as the bed material. The average diameter of elutriated fine particles were 81, 97, 115, 137, 163, and 193 μm. The average diameter of coarse glass beads of which terminal velocity larger than the superficial gas velocity was 545 μm. The properties of the glass beads used in this experiments are summarized in Table 1. A cyclone was used to capture the elutriated fine particles from the column.

The primary air and secondary air were supplied by two 15-hp roots blowers, respectively. The air flow rates were measured by orifice plates. The primary air passed through a humidifier to regulate the humidity in order to decrease the electrostatic effect on the particles. The secondary air was separated equally into four streams and horizontally injected into the freeboard. The primary air velocity ranged from 0.88 to 1.76 m/s; the gas velocity of the secondary air through the injection nozzles ranged from 7.35 to 22.0 m/s. The operating conditions are

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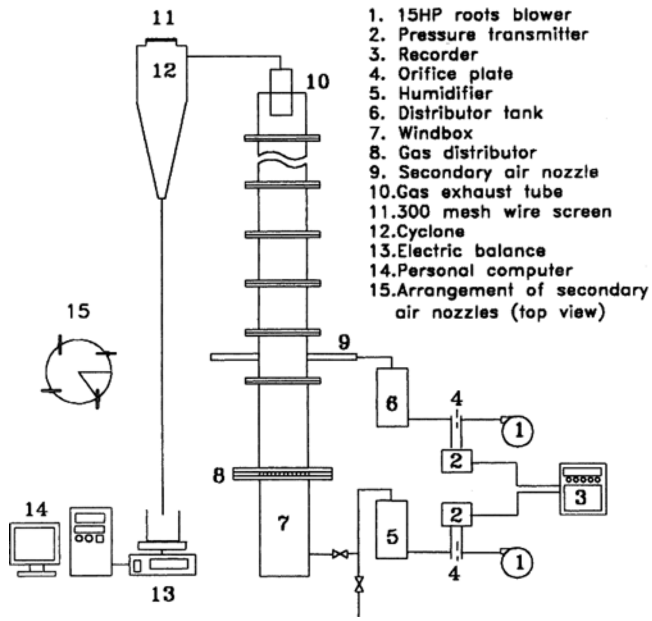

Fig. 1. Schematic diagram of the experimental apparatus.

Table 1. Experimental conditions

Parameter	Unit	Magnitude
Primary air velocity	m/s	0.88-1.76
Secondary air velocity	m/s	7.35-22.0
Fine particle diameter	μm	81-193
2^{nd} air nozzle injection height	m	4.0-8.0 D_o
Injected angle of 2^{nd} air nozzle	°	0-15

Table 2. Relevant properties of glass beads used in the experiments

Particle size (μm)	Density (kg/m^3)	U_{mf} (m/s)	U_t (m/s)
193	2420	0.030	1.188
163	2420	0.021	0.980
137	2420	0.015	0.804
115	2420	0.011	0.659
97	2420	0.0075	0.542
81	2420	0.0052	0.442

summarized in Table 2.

An electronic balance (OHAUS TP4KD) was used to weigh the fine particles, which were elutriated from the column and captured by the cyclone. The elutriated fine particles fell into the beaker which was placed on the electric balance. The accumulate weight of the elutriated fine particles in the beaker was continuously measured by electronic balance and the data measured were transferred to a personal computer by using a RS232 interface card. The time interval of data transferred to the personal computer was two seconds. The operating time of each run was determined by ensuring that there would still be about 10 wt% of the original fraction of the fine particles remaining in the bed [Geldart, 1986].

In this study, the specific elutriation rate constant proposed by Wen and Hashinger [1960] was used to describe the elutriation rate:

$$\frac{dC}{dt}=-K_\infty^*\frac{A}{W}C \qquad (1)$$

where: $K_\infty^*=\frac{kW}{A}$

RESULTS AND DISCUSSION

1. Effect of Primary Air Velocity

From Fig. 2, we can find that the specific elutriation rate constant (K_∞^*) increases exponentially with the primary air velocity. From a previous study, we know that the primary air velocity is the dominant factor for the rate of elutriation in a vortexing fluidized bed [Chyang et al., 1998].

Besides, the swirling flow caused by the secondary air tangentially injected into the freeboard. As a result, particles entrained to the freeboard hit the column wall and then fall back into bed. From Fig. 2, the specific elutriation rate constant (K_∞^*) increases exponentially with the primary gas velocity and de-creases significantly by the swirling flow.

The specific elutriation rate constant (K_∞^*) of the VFB can be almost one order of magnitude lower than that of the conventional BFB as shown in Fig. 2.

2. Effect of Secondary Air Injection

2-1. Effect of Secondary Air Velocity

For a given primary air flow rate and secondary air flow rate, it is shown that the specific elutriation rate constant (K_∞^*) decreases with the secondary air velocity, as shown in Fig. 3. This can be attributed to the effect of swirling stream caused by the tangentially injected secondary air on the specific elutriation rate constant (K_∞^*). The intensity of the swirling flow increases with the velocity of secondary air in the 'swirling effect zone (SEZ)' [Wan and Chyang, 1998]. Therefore, the amount of fine

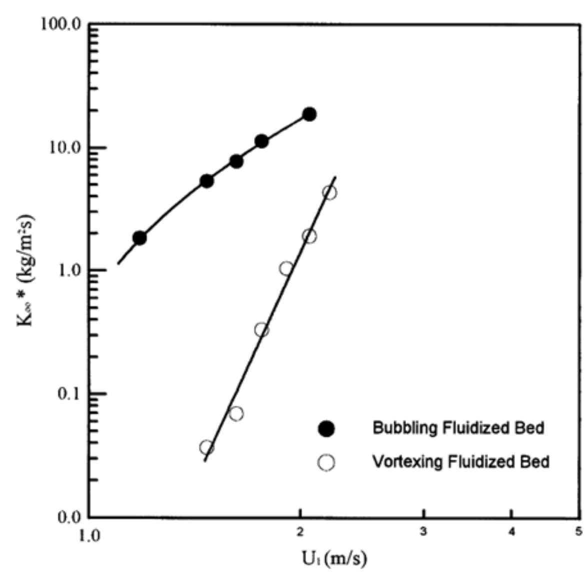

Fig. 2. Effect of superficial gas velocity on specific elutriation rate constant with and without secondary air injetion. (C_o=10 wt%, $d_{p,c}$=545 μm, $d_{p,f}$=115 μm; U_2=0 m/s in the BFB, U_2=7.4 m/s in the VFB)

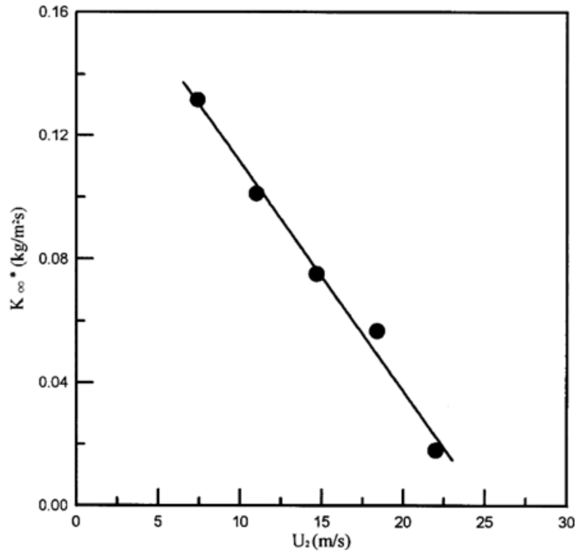

Fig. 3. Effect of secondary air velocity on specific elutriation rate constant in the VFB.
(U_1=1.08 m/s, C_o=10 wt%, $d_{p,c}$=545 μm, $d_{p,f}$=115 μm)

particles elutriated decreases with the secondary air velocity.

2-2. Effect of Secondary Air Nozzle Injection Angle

The geometric arrangement of the secondary air nozzles in the vortexing fluidized bed can be characterized by the secondary air nozzle injection angle (imaginary circle) [Nieh et al., 1992]. The imaginary circle is defined as an internal tangent circle enclosed by the secondary nozzles. The diameter of the imaginary circle can be varied by changing the injection angle of the nozzles.

From Fig. 4, a analogous hyperbola relationship can be found between the specific elutriation rate constant (K_∞^*) and the injection angle of the secondary air nozzle. When the secondary air injection angle is 60°, the specific elutriation rate constant (K_∞^*) reaches its minimum value. In our previous study [Chyang et al., 1997], the maximum value of swirl intensity (vortex number, V_{or}) is obtained when the angle of the secondary air injection equals to 60°. Comparing the results of swirl intensity and particle elutriation rate, we can infer that the more strong swirl flow, the lower values of elutriation rate that can be obtained.

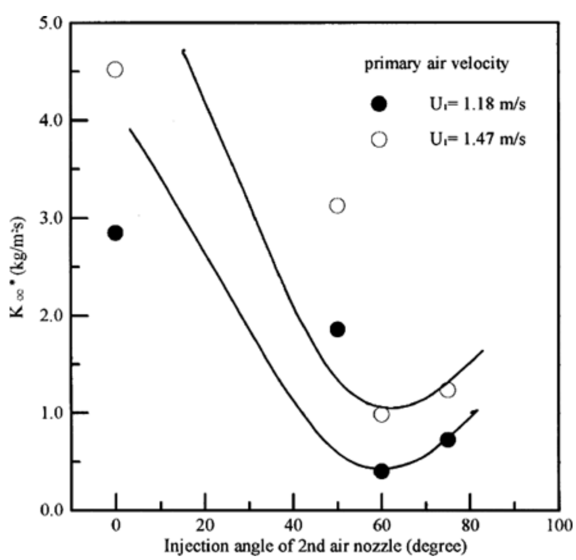

Fig. 4. Efect of the secondary air injection angle on the specific elutriation rate constant with various primary air velocities in the VFB.
(U_2=22 m/s, C_o=10 wt%, $d_{p,c}$=545 μm, $d_{p,f}$=115 μm)

3. Effect of the Diameter of Fine Particles

Because of the swirling flow caused by the secondary air tangentially injected into the freeboard in the VFB, particles entrained to the freeboard hit the column wall and then fall back into the bed. Therefore, the elutriation rate of the VFB decreases significantly over that of a conventional BFB. The primary air velocity and the diameter of fine particles are both dominant factors in the elutriation behavior.

From Fig. 5, we can find that the specific elutriation rate constant (K_∞^*) decreases as the diameter of the fine particles increases. Owing to the elutriation rate's dependence on the primary air velocity and the diameter of fine particle, that is, dependence on (U_o-U_t), the elutriation rate decreases as the particle terminal velocity increases in the same primary air velocity.

4. The Taguchi Experimental Method and Regular Analysis

The method of experimental design is a useful tool for understanding the relationship between the operating variables. One of the approved methods employed frequently is the method of the full factorial experiment. However, it is very complicated in that the procedure of the full factorial experiment must examine each factor. In the 1980s, a new experimental design method, proposed by Taguchi [1986], provided a convenient method for analyzing many factors by using a very small number of observations.

According to the effect of experimental parameters on the elutriation rate constant (K_∞^*), we can distinguish the significance between the parameters by using the Taguchi experimen-

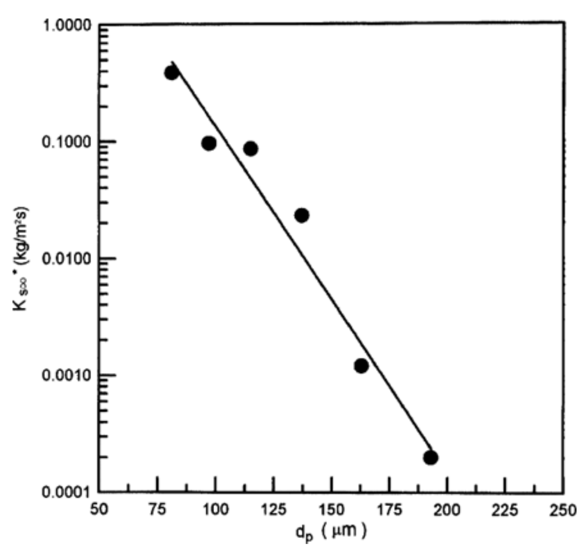

Fig. 5. Effect of diameter of fine particles on specific elutriation rate constant.
(U_1=1.18 m/s, U_2=22 m/s, H_s=3.0 D_o m, $d_{p,c}$=545 μm)

Table 3. Experimental conditions and data applied to an orthogonal array $L_9(3^4)$

Factor no.	Orthogonal array $L_9(3^4)$				Experimental conditions				Results
	A	B	C	D	U_1	U_2	d_p	H_s	K_∞^*
	1	2	3	4	m/s	m/s	μm	D_o	
1	1	1	1	1	0.88	7.35	81	4	0.0324
2	1	2	2	2	0.88	14.7	115	6	0.0049
3	1	3	3	3	0.88	22.0	137	8	0.0012
4	2	1	2	3	1.18	7.35	115	8	0.1542
5	2	2	3	1	1.18	14.7	137	4	0.1064
6	2	3	1	2	1.18	22.0	81	6	0.3964
7	3	1	3	2	1.47	7.35	137	6	0.1245
8	3	2	1	3	1.47	14.7	81	8	0.4862
9	3	3	2	1	1.47	22.0	115	4	0.3501

Table 4. The regular analysis of experimental data by using an orthogonal array $L_9(3^4)$

Level of factor	The sum of level	Average	Level of factor [max.-min.]	Effect of signification
A_1	0.0385	0.0128		
A_2	0.657	0.2190	0.9223	6.04
A_3	0.9608	0.3203		
B_1	0.3111	0.1037		
B_2	0.5975	0.1992	0.4366	2.86
B_3	0.7477	0.2492		
C_1	0.9150	0.3050		
C_2	0.5092	0.1697	0.6829	4.47
C_3	0.2321	0.0774		
D_1	0.4889	0.1630		
D_2	0.5258	0.1753	0.1527	1
D_3	0.6416	0.2139		

tal method and Regular analysis. An orthogonal array $L_9(3^4)$, i.e., nine observations (experiments) and at most four factors (variables) each at three levels (operating conditions), was taken in this case. The factors studied were primary air velocity, secondary air velocity, particle diameter, and the injection height of secondary air nozzle, with three conditions each. The experimental data obtained for analyzing were the elutriation rate of fine particles.

Table 3 is the experimental factors and conditions applied to an orthogonal array $L_9(3^4)$. Parameters such as primary air velocity, secondary air velocity, particle diameter, and the injection height of secondary air nozzle were used in this analysis. From Table 4, we can see that the significance of the parameters on the elutriation rate constant (K_∞^*) was sorted as follows: primary air velocity (6.04)>particle diameter (4.47)>secondary air velocity (2.86)>the injection height of secondary air nozzles (1.0).

This indicates that the primary air velocity is the most important factor to dominate elutriation rate, then that of particle diameter, secondary air velocity, and the injection height of secondary air nozzles.

5. The Correlation of Specific Elutriation Rate Constant

From the results obtained above, it is necessary to correlate a new specific elutriation rate constant (K_∞^*) equation. Based on the experimental data obtained in a VFB system, an attempt is made to correlate the specific elutriation rate constant (K_∞^*) in terms of appropriate characteristic parameter, such as primary air velocity, particle diameter, secondary air velocity, and the injection height of secondary air nozzles. By using dimensional analysis and regression analysis, a relation is proposed as:

$$K_\infty^* = 10^{7.2} U_1^{7.8} U_2^{-0.4} d_p^{-3.7} \left(\frac{H_s}{D_o}\right)^{-1.3} \qquad (2)$$

When : $0.88\ \text{m/s} \le U_1 \le 1.47\ \text{m/s}$
$7.35\ \text{m/s} \le U_2 \le 22.0\ \text{m/s}$
$81\ \mu\text{m} \le d_p \le 137\ \mu\text{m}$
$4 \le H_s/D_o \le 8$

In Fig. 6, the K_∞^* estimated from Eq. (2) are compared with the experimental data. The average deviation and standard deviation are 24.6% and 28.3%, respectively.

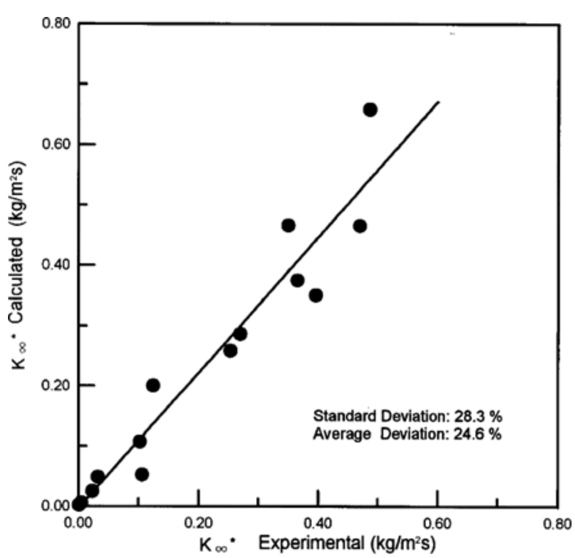

Fig. 6. Comparison between calculated specific elutriation rate constant and value measured in a vortexing fluidized bed.

CONCLUSIONS

The effects of swirling flow on the elutriation rate have been studied in this paper. It is found that the elutriation rate constant (K_∞^*) decreases significantly by the swirling flow. It also found that the elutriation rate constant (K_∞^*) increases with primary air velocity, and decreases with the secondary air velocity and the fine particle diameter. The minimum value of the elutriation rate constant (K_∞^*) is obtained when the injection angle of second-ary air equals to 60°.

By using the Taguchi experimental method and Regular analysis, we find that the significance of the parameters on the elutriation rate constant (K_∞^*) is sorted as primary air velocity, particle diameter, secondary air velocity, and the injection height of secondary air nozzle. An empirical correlation for estimating the specific elutriation rate constant in a VFB has been presented. The specific elutriation rate constant is a function of primary air velocity, secondary air velocity, diameter of fine particle, and the height of secondary air injection.

NOMENCLATURE

A : cross sectional area of bed [m^2]
C : fine particle concentration in bed [-]
D_o : fluidized bed column diameter [m]
d_p : mean diameter of particles [μm]
$d_{p,f}$: fine particles mean diameter [μm]
$d_{p,c}$: coarse particles mean diameter [μm]
E : elutriation rate of particles [kg/m^2s]
H_s : the injection height of secondary air nozzle [m]
K_∞^* : specific elutriation rate constant [kg/m^2s]
t : time [sec]
U_o : superficial gas velocity in the BFB [m/s]
U_t : terminal velocity of particle [m/s]
U_1 : primary air velocity in the VFB [m/s]
U_2 : secondary air velocity in the VFB [m/s]
W : weight of particle in bed [kg]

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