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NOTE

AXIAL VOIDAGE PROFILE IN A COLD MODEL CIRCULATING FLUIDIZED BED

Jeong-Hoo CHOI, Chang-Keun YI and Jae-Ek SON

Waste Resources Utilization Laboratory, Korea Institute of Energy and Resources,
P.O. Box 5, Daeduck Science Town, Daejeon, Korea, 305-606, Korea
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Abstract—The axial voidage profile was measured in a cold model circulating fluidized bed (0.38 m in diameter and 9.1 m in height) of sand particles as bed materials. Voidage in the riser column increases along the height above the distributor plate with increasing the gas velocity. However, it decreases with an increase in solid circulation rate in the bed. Model correlations to predict the solid circulation rate and the axial voidage profile in the bed are proposed.

INTRODUCTION

The circulating fluidized bed combustion technology has been successfully commercialized since it has high combustion efficiency with various fuels, the high sorbent utilization efficiency and the effective reduction of NO_x. The axial density profile of circulating fluidized bed combustor is an important factor to predict the particle distribution and solid load in the furnace, heat transfer rate on the furnace wall, freeboard combustion and so on [1,2].

The voidage or density of circulating fluidized bed has been reported in previous studies [3-7]. However, most of data were obtained in small column diameters of fine particles with an excessive solid circulation rate. Therefore, they are not suitable to characterize the particle flow pattern in the large circulating fluidized bed combustor which employs coarse particles with a low solid circulation rate. In case of Studsvik/B&W's boiler, the solid circulation rate was 10-15 kg/m^{2}s in the full load [1], which is much smaller than the value of fine particle systems ranging from several tens to a hundred kg/m^{2}s. Also, the solid loading of the upper part of the combustor where the heat transfer surface was placed ranged from 4 to 90 kg/m^3 approximately. Such a solid loading lies in the range of dilute phase.

This study measured the axial voidage profile in a 0.38m-ID cold model circulating fluidized bed of sand particles belong to the Geldart group B powder. In addition, model correlations are proposed for the solid circulation rate and the axial voidage profile.

*Author to whom all correspondence should be addressed.

EXPERIMENTAL

The schematic diagram of a cold model circulating fluidized bed used for the experiment can be seen in previous reports [8,9]. The fluidized bed unit consisted of a riser column and the recycle parts. The riser column, made of transparent acrylic resin, was 0.38 m in diameter and 9.1 m high from the distributor plate to the gas exit level. Fifteen pressure taps were mounted on the wall of the column axially and connected to 5 pressure transducers. A perforated plate was used as a distributor which contained 1963 holes of 3 mm in diameter. The recycle parts consisted of two cyclones in series, two reservoirs and a rotary valve with a variable speed motor. The rotary valve controlled the solid circulation rate in the circulating fluidization condition. The solid particles were fluidized by ambient air which was supplied from a forced draft fan.

Sand was used as the bed material to reduce particle attrition in the experimental analysis. The apparent and bulk densities of sand were 2.63 g/cm^3 and 1.35 g/cm^3 respectively. Two particle size distributions of sand employed is shown in Table 1. The specific surface mean diameters of sand were 0.41 mm and 0.26 mm, respectively.

In the experiments, the axial differential pressure profile with the variation of gas velocity and solid circulation rate in the riser column was measured by pressure transducers. The output signal from the pressure transducer was processed by a Apple II micro-

Table 1. Size distributions of sand

Mesh range (mm)	- 1.41 +0.71	- 0.71 +0.59	- 0.59 +0.42	- 0.42 +0.25	- 0.25 +0.177	- 0.177 +0	Mean size (mm)
Weight fraction:							
Sand A	0.015	0.020	0.605	0.310	0.041	0.009	0.410
B	0.015	0.060	0.241	0.416	0.125	0.143	0.260

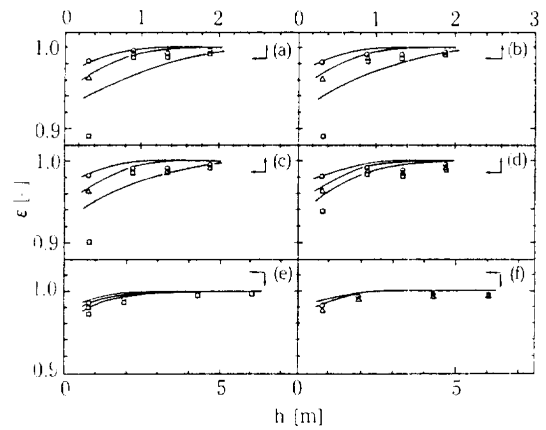

Fig. 1. Effect of the gas velocity on the axial voidage profile [refer to Table 2 for symbol descriptions; solid line - cal. values by Eqs. (5) to (5.6)].

computer and recorded on a strip chart recorder. The interval of signal acquisition in the computer was 0.0234 sec.

RESULT AND DISCUSSION

1. Measured axial voidage profile

The axial voidage profile of the riser column was determined by measuring the axial differential pressure profile. According to previous works [4,10,11], the differential pressure ($\Delta p/\Delta h$) exhibited a linear proportion to the solid concentration and the effect of frictional loss among the particles and the column wall could be neglected in the present column diameter of 0.38 m. Then the bed voidage can be expressed as

$$\epsilon_s = \frac{g_c}{g}\frac{\Delta p}{\Delta h}\frac{1}{\rho_s} \tag{1}$$

$$\epsilon = 1 - \epsilon_s. \tag{2}$$

Figure 1 shows the measured axial voidage profile of the riser column of sand A and B with the variation of the gas velocity at a given solid circulation rate. As can be expected, the bed voidage, $(1-\epsilon_s)$, increased with the height above the distributor. That may indicate the presence of dense phase at the lower part and the dilute phase at the upper part of the column.

Table 2. Symbol descriptions for Figures 1 and 2

Figure	Sand			O	Δ	□
1(a)	A	G_s = 3 [kg/m²s]	U[m/s]:	3.27	3.06	2.86
(b)	A	5.1		3.47	3.27	3.16
(c)	A	7.1		3.67	3.47	3.37
(d)	A	9.2		4.08	3.87	3.67
(e)	B	12.1		4.70	4.43	3.83
(f)	B	14.1		4.62	4.37	
2(a)	A	U = 3.27 [m/s]	G_s[kg/m²s]:	3.0	5.1	
(b)	A	3.47		5.1	7.1	
(c)	A	3.67		7.1	9.2	

The axial voidage profile is affected by various combined factors such as the influx of recycled particles at the lower part, the bed expansion, entrainment of particles, the down-flow of particles by the wall effect and so on. Meanwhile, from the view-point of solid circulation, the present profile would show that the rising velocity of solid over the cross-section increased with the height above the distributor due to the reduction of solids down-flow, while the solid circulation rate is represented as

$$G_s = \epsilon_s u_s \rho_s = (1-\epsilon) u_s \rho_s \tag{3}$$

where u_s is the rising velocity of solid.

Also, the bed voidage, $(1-\epsilon_s)$, increases with increasing the gas velocity as shown in Figure 1. It may be due to the increase of the solid rising velocity with increasing the gas velocity and consequent decrease in the solid holdup, as can be expected qualitatively from Eq. (3).

Figure 2 shows the effect of solid circulation rate on the axial voidage profile of the riser column of sand A as the bed material at a given gas velocity. The bed voidage, $(1-\epsilon_s)$, decreases with an increase in solid circulation rate. According to Eq. (3), the solid holdup and the rising velocity of solid would increase with in-

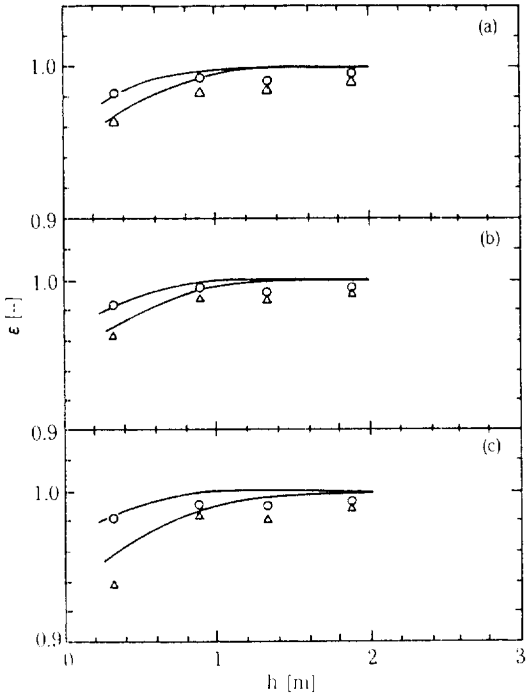

Fig. 2. Effect of the solid circulation rate on the axial voidage profile [refer to Table 2 for symbol descriptions; solid line - cal. values by Eqs. (5) to (5.6)].

creasing the solid circulation rate.

2. Solid circulation rate

The solid circulation rate is a basic information for the circulating fluidized bed. In previous studies [8,9,12], entrainment of solids at the freeboard gas off-take position of the column size ranging from 0.25m to 0.91m in diameter was discussed by a model. Their model also predicts the solid circulation rate fairly well in the column size of 0.4m-ID of Hartge et al. [5].

However, most of the reported data has been obtained in the smaller column diameters of fine particles. Meanwhile, the effect of column size on the solid circulation rate seems to be nonlinear in previous studies [4,5] although it is difficult to draw any definite conclusion. As a result, the reported solid circulation rates [3-5,7,13], obtained in the columns smaller than 0.2m-ID, could be predicted by the following correlation of the entrainment flux of the bed surface within 41% mean deviation based on the model of Choi et al. [12].

$$E_o = 2.64\, d_t^{-0.799} (U - U_{mf})^{1.21} H_e^{0.460}, \quad r^2 = 0.81 \qquad (4)$$

where the range of variables is $0.04 < d_t[m] < 0.20$, $0.8 < U[m/s]$ 7, $0.03 < H_s[m] < 2,22$, and $1700 < \rho_s[kg/m^3] < 4510$. The entrainment flux is inversely proportional to the column diameter as can be seen in the above correlation. But the entrainment flux was proportional to the square of column diameter between 0.25m and 0.91m [9,12].

3. Correlations of the axial voidage profile

The axial voidage profile has been correlated with the experimental variables as shown in Eqs. (5) to (5.6). The expanded bed height(H_e) was calculated at a given static bed height using the two-phase theory [9]. The resulting correlations of present experimental data and the reported data [3-5, 7, 13] are as following:

$$\frac{1-\epsilon}{\epsilon + 0.55\dfrac{H_s}{H_e} - 1} = \exp[-F_0\{(h - H_e) - F_1\}], \quad r^2 = 0.863 \qquad (5)$$

$$F_0 = 0.0576 \frac{(U - U_{mf})^{1.74} G_s^{1.07}}{\rho_s^{1.40} d_t^{0.448} H_s^{1.50}}, \quad \text{if } h < H_s \qquad (5.1)$$

$$F_0 = 884 \frac{(U - U_{mf})^{2.31} G_s^{0.234}}{\rho_s^{2.11} d_t^{0.441} H_s^{1.38}}, \quad \text{if } H_s < h < H_e \qquad (5.2)$$

$$F_0 = 0.0277 \frac{d_t^{1.68} G_s^{0.571}}{(U - U_{mf})^{1.73} H_s^{0.761}}, \quad \text{if } H_e < h \qquad (5.3)$$

$$F_1 = -5.06 \times 10^{11} \frac{(U - U_{mf})^{1.03} G_s^{2.95}}{\rho_s^{7.93} d_t^{1.45} H_s^{6.37}}, \quad \text{if } h < H_s \qquad (5.4)$$

$$F_1 = -8.72 \times 10^{-19} \frac{(U - U_{mf})^{0.393} \rho_s^{4.23}}{G_s^{0.228} d_t^{3.12} H_s^{1.46}}, \quad \text{if } H_s < h < H_e \qquad (5.5)$$

$$F_1 = -360 \frac{(U - U_{mf})^{4.22} H_s^{1.12}}{\rho_s^{0.961} d_t^{4.72} G_s^{1.99}}, \quad \text{if } H_e < h \qquad (5.6)$$

where the range of variables is $0.04 < d_t[m] < 0.4$, $0.6 < U[m/s] < 7$, $0.03 < H_s[m] < 2.22$, $2.5 < G_s[kg/m^2s] < 600$, and $1700 < \rho_s[kg/m^3] < 4510$. In above correlations, U_{mf} was calculated by using the correlation of Wen and Yu [14].

$$U_{mf} = \frac{\mu}{d_p \rho_g} \left(\left\{ (33.7)^2 + 0.0408 \frac{d_p^3 \rho_g (\rho_s - \rho_g) g}{\mu^2} \right\}^{0.5} - 33.7 \right) \qquad (6)$$

CONCLUSION

The axial voidage profile of the riser was measured in a cold model circulating fluidized bed of sand particles as the bed material and the following conclusion can be drawn:

1. The bed voidage in the column increases with the height above the distributor and the gas velocity.

However it decreases with an increase in the solid circulation rate.

2. Model correlations for the axial voidage profile and for the solid circulation rate of a column smaller than 0.2m in diameter are proposed.

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NOMENCLATURE

d_p : mean particle diameter [m]
d_t : column diameter [m]
E_0 : entrainment flux at the bed surface [kg/m^2·s]
g : gravitational acceleration [m/s^2]
g_c : conversion factor [kg·m/kg$_f$·s^2]
G_s : solid circulation rate [kg/m^2·s]
h : height above the distributor [m]
H_e : expanded bed height [m]
H_s : static bed height [m]
$\Delta p/\Delta h$: bed denisty measured by pressure transducers [kg/m^3]
r^2 : regression coefficient [–]
U : superficial gas velocity [m/s]
U_{mf} : minimum fluidizing gas velocity [m/s]
u_s : rising velocity of solid [m/s]
μ : gas viscosity [Pa s]
ϵ : voidage [–]
ϵ_s : solid holdup [–]
ρ_g : gas density [kg/m^3]
ρ_s : solid density [kg/m^3]

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