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HYDRODYNAMIC PROPERTIES OF COAL IN TURBULENT FLUIDIZED BEDS

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Abstract—Hydrodynamic properties in turbulent fluidized beds of three different sizes of coal (d_p = 0.507, 0.987, 1.147 mm) have been determined from the pressure fluctuations in a 0.1 m-ID × 3.0 m high Plexiglas column. The transition velocity from the slugging to turbulent flow regimes can be determined from the statistical analysis of pressure fluctuations such as mean amplitude, standard deviation and skewness, the pressure wave velocity, and the bed expansion with gas velocity. The bed expansion in the slugging and turbulent flow regimes cannot be estimated from the two-phase theory. The voids rise velocity and the bed expansion ratio (H/H_{mf}) in the turbulent flow regime have been correlated with the relevant dimensionless and operating parameters

$$V_t = 40.66\,Ar^{-0.280}\,[0.35\,(gD_t)^{1/2}] - U_{mf}$$

$$\frac{H}{H_{mf}} = 1 + 10.805\,Ar^{-0.290}\,\left(\frac{U_g - U_{mf}}{V_t}\right)^{0.635}$$

The transition velocity to the turbulent flow regime has been determined based on the slug breakdown caused by the inertial force of an upflowing maximum stable slug which overcomes the gravitational force induced by solid refluxing as:

$$Re_c = [(33.7)^2 + 0.0408\,Ar]^{1/2} + 0.598\,Ar^{1/2} - 33.7$$

INTRODUCTION

A further increase in gas velocity beyond the slugging flow regime starts the turbulent flow regime which is characterized by the breakdown of larger bubbles or slugs into smaller voids in the bed. This high velocity fluidized bed operation has received considerable attention in recent years due to the great contacting capabilities between the gas and solid phases in the catalytic and non-catalytic reaction systems.

Therefore, combustion of coal in the high velocity fluidized beds is subjected to research since it proves to have many advantages for coal utilization such as fuel flexibility, high combustion efficiency, high sulfur retention, lower NO_x emission, easy fuel handling, high heat release rate, high turndown ratio or load [1-3]. In addition, a high velocity fluidized bed combustor has been operated to generate a total of 2100 MWe by a combined cycle system with gas and steam turbines [4].

Information on the hydrodynamic properties in the high velocity fluidized bed of coal particles are needed to design the combustors and to evaluate the operating performance. Therefore, in the present study, the hydrodynamic properties such as the pressure fluctuations, voids rise velocity and the bed expansion have been determined in a turbulent fluidized bed of coal. In addition, the transition velocity to the turbulent flow regime has been derived based on the Froude number criteria.

EXPERIMENTAL

Experiments were carried out in a Plexiglas column of 0.1 m-ID×3.0 m high as shown schematically in Fig. 1. Three mean sizes of coal (0.507, 0.987, 1.147 mm) with a density of 1407 kg/m^3 were fluidized by compressed air. The mean size and its distribution have been determined from sampled bed material at three different vertical positions in the beds. The size distributions of these particles and the corresponding histogram are shown in Table 1 and Fig. 2, respective-

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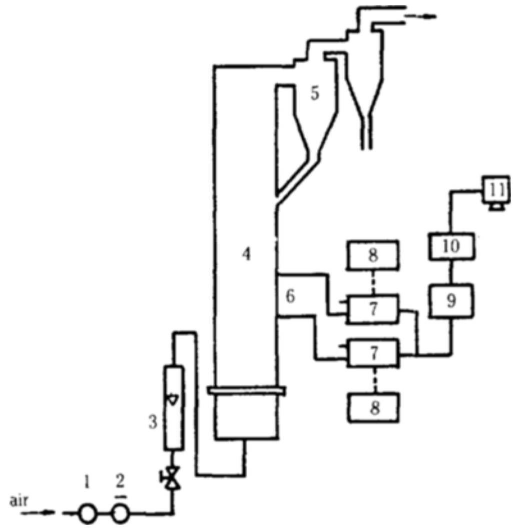

Fig. 1. Schematic diagram of experimental apparatus.

1: oil filter 2: pressure regulator
3: rotameter 4: fluidized bed
5: cyclone 6: probe
7: pressure transducer 8: D.C. power supplier
9: amplifier 10: A/D converter
11: personal computer

Table 1. Physical properties of coal

Particle size (mm)	Weight fraction (wt %)		
	C-1	C-2	C-3
2.00-1.68	·	4.63	
1.68-1.41	·	12.38	0.50
1.41-1.19	·	13.01	41.05
1.19-1.00	·	19.72	43.22
1.00-0.84	·	10.92	9.82
0.84-0.71	0.70	8.72	5.08
0.71-0.59	6.67	10.47	0.33
0.59-0.50	57.85	9.61	·
0.50-0.42	19.54	6.63	·
0.42-0.30	13.82	3.91	·
0.30-0.21	1.42	·	·
mean size (mm)	0.507	0.987	1.147
standard deviation of distribution (mm)*	0.084	0.395	0.157
minimum fluidizing gas velocity (m/s)	0.08	0.15	0.22
voidage at U_{mf} (ε_{mf})	0.55	0.55	0.60

particle density: 1407 kg/m^3

$$*\sigma = \left\{ \frac{\sum_i [w_i (d_{pi} - d_p)^2]}{\sum_i w_i} \right\}^{1/2}$$

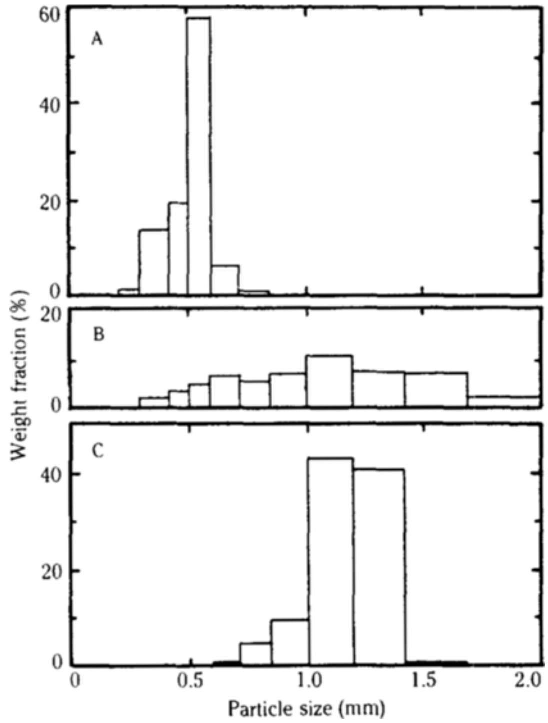

Fig. 2. Histogram of particle size distribution.
A: C-1, B: C-2, C: C-3

ly. These particles are classified by the narrow (C-1 and C-3) and wide size distributions (C-2). In the present study, the solid particles were supported on a bubble cap distributor plate which was situated between the main column and the air box into which air was fed to the column through an oil filter, a pressure regulator and a calibrated rotameter. The entrained solid particles from the bed were collected by the primary and secondary cyclones in series and were recycled to the main bed simultaneously. The column was initially loaded with 6.5 kg of coals giving a static bed height of 1.0 m. The pressure fluctuations in the bed were measured by means of pressure transducers (Fisher Controls Co., 1151). The continuous pressure signals from the transducer were amplified and sent them via an A/D converter to a personal computer (Apple IIe) for recording. The sampling interval of the fluctuations was selected at 10 ms and 8192 samples were collected for each experimental conditions. The rise velocities of slugs and voids in the slugging and turbulent flow regimes have been determined from the cross-correlation between two fluctuation signals. The bed voidage, ε, and the bed expansion ratio, H/H_{mf}, have been determined from the measured mean pressure drop in the bed as:

$$\Delta P/\Delta L = \rho_s(1-\epsilon)g \quad (1)$$

$$H/H_{mf} = (1-\epsilon_{mf})/(1-\epsilon) \quad (2)$$

The details of the experimental setup and the experimental procedures are described in previous studies [5,6].

RESULTS AND DISCUSSION

1. Statistical properties

The transition to the turbulent flow regime has been determined from a point at which the mean amplitude of pressure fluctuations with gas velocity begins to level-off [5,7,8].

The mean amplitude of pressure fluctuations with gas velocity at 0.53 m above the distributor plate is shown in Fig. 3. As can be seen, the mean amplitude of pressure fluctuations goes to a maximum value, and then it decreases with an increase in gas velocity. This maximum point can be regarded as the onset to the turbulent flow regime in the bed. The transition velocities to the turbulent flow regime are found to be 0.62, 0.81 and 1.09 m/s for the C-1, C-2 and C-3 particles, respectively. Moreover, the mean amplitude in the transition region to the turbulent flow regime of the C-2 particles appears to be higher than that of the C-1 and C-3 particles. This may indicate that the pressure fluctuations in the bed of wide size distribution particles have a higher amplitude than in the bed of narrow size distribution particles. This may be caused by the higher resistance of percolating gas through the interstices of solid particles with wide size distribution in more densely packed state.

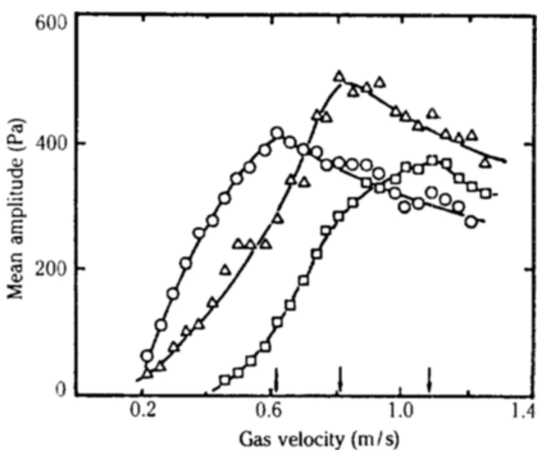

Fig. 3. Mean amplitude of pressure fluctuations with gas velocity.
○: C-1, △: C-2, □: C-3

Variations of standard deviation in the pressure fluctuations with gas velocity are shown in Fig. 4. As can be seen, the variation of standard deviation with gas velocity is similar to the mean amplitude (Fig. 3). Moreover, the transition region of each particles with gas velocity can be observed at a similar value with the variation of mean amplitude.

Variation of the skewness in pressure fluctuations with gas velocity is shown in Fig. 5. As can be seen, the value of skewness is almost constant in the slugging flow regime, but it increases with an increase in gas velocity in the turbulent flow regime. The transition point of skewness with gas velocity is an onset to the turbulent flow regime [5]. There appears that

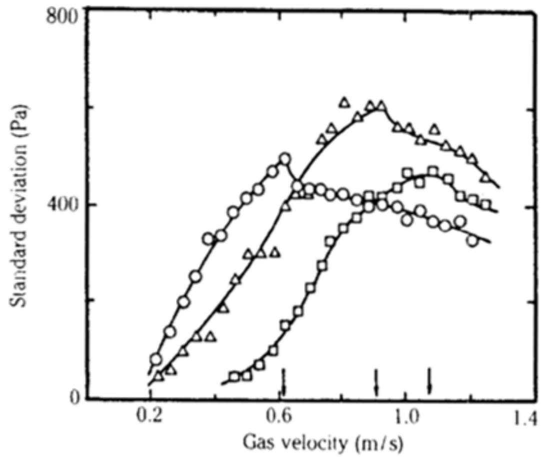

Fig. 4. Standard deviation of pressure fluctuations with gas velocity.
○: C-1, △: C-2, □: C-3

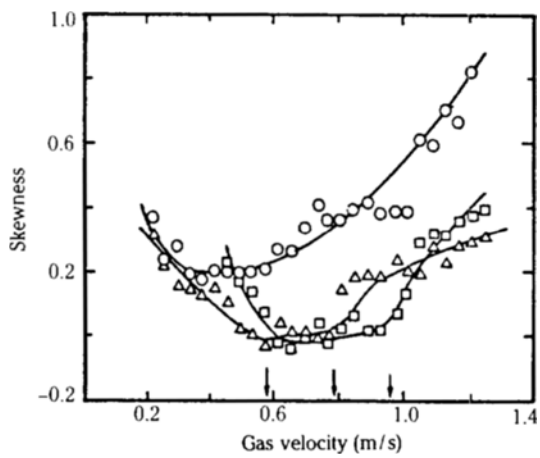

Fig. 5. Skewness of pressure fluctuations with gas velocity.
○: C-1, △: C-2, □: C-3

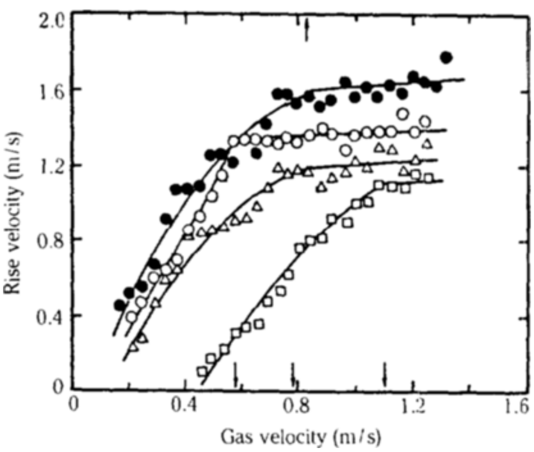

Fig. 6. Rise velocities of slugs and voids with gas velocity in the slugging and turbulent flow regimes.
○: C-1, △: C-2, □: C-3, ●: Lee and Kim [6]

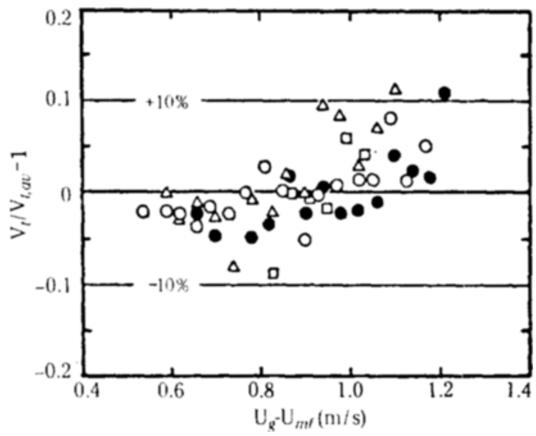

Fig. 7. Variation of voids rise velocity deviated from average value with gas velocity.
○: C-1, △: C-2, □: C-3, ●: Lee and Kim [6]

Table 2. A summary of experimental conditions and results of voids rise velocity in the turbulent flow regime

Workers	D_t (m)	Particles	d_p (μm)	ρ_s (kg/m^3)	U_{mf} (m/s)	V_t (m/s)
Fan et al.	0.203	sand	1122	2650	0.66	1.14
[9]			711	2640	0.36	1.24
			491	2620	0.20	1.34
		glass beads	491	2430	0.28	1.54
			358	2400	0.16	2.12
Lee and Kim [6]	0.10	glass beads	362	2500	0.11	1.60
present	0.10	coal	508	1407	0.08	1.37
study			987		0.15	1.20
			1147		0.22	1.10

the transition velocities to the turbulent flow regime from the variation of skewness with gas velocity are similar to those obtained from the mean amplitude and the standard deviation of pressure fluctuations.

The skewness is a non-dimensionalized third central moment which is a measure of the lack of symmetry in the probability density function about the mean of fluctuation signals. The increase in skewness in the turbulent flow regime is caused by the increase of small fluctuations in solid phase due to the breakdown of slugs into smaller bubbles in the bed [5] As can be seen, the value of skewness of the C-1 particles is larger than that of the C-2 and C-3 particles. This may indicate that the voids movement in the dense phase is more vigorous in the bed of smaller particles.

2. Voids rise velocity

The velocity of pressure fluctuation waveform can be defined by the rise velocity of bubbles in the bed [6,9]. In the present study, the rise velocities of slugs and voids in the slugging and turbulent flow regimes have been determined from the transit time of pressure fluctuations at which the cross-correlation function of fluctuation signals between the two measuring points (0.53 and 0.63 m above the distributor plate) has a maximum value.

The rise velocity of slugs or voids increases with an increase in gas velocity in the slugging flow regime, but it appears to be almost constant in the turbulent flow regime (Fig. 6). The rise velocities in the turbulent flow regime are within ±10% of the average value (Fig. 7). Therefore, the voids rise velocity in the turbulent flow regime is found to be almost constant in beds of coarse particles [6,9]. Moreover, the gas velocities corresponding to the transition points in the rise velocity are very similar to the values reported previously (Figs. 3, 4 and 5). Therefore, the transition velocity to the turbulent flow regime can be determined from the rise velocity of slugs or voids. A summary of the experimental conditions and corresponding results of the present and previous studies on the voids rise velocity in the turbulent flow regime is shown in Table 2. As can be seen, the voids rise velocity decreases with increasing particle size and density. The rise velocity of voids increases with increasing column size due to the reduction in wall-effect [6]. The voids rise velocity in the turbulent flow regime has been correlated as:

$$V_t = 40.66 Ar^{-0.280} [0.35 (gD_t)^{1/2}] - U_{mf} \quad (3)$$

where $Ar = d_p^3 \rho_g (\rho_s - \rho_g) g / \mu^2$

This correlation covers the range of variables $3.40 \times 10^6 \leq Ar \leq 1.16 \times 10^8$ and $10.0 \leq D_t \leq 20.3$ with a correlation coefficient of 0.82 based on the data of Table 2.

3. Bed expansion

Bed expansion in fluidized beds has been generally represented by the Richardson-Zaki's equation [10] as:

$$\frac{U_g}{U_t} = \epsilon^n \quad (4)$$

where U_t is terminal velocity of an individual particle.

The logarithmic plot of bed voidage with gas velocity is shown in Fig. 8. As can be seen, the bed voidage increases with an increase in gas velocity in which the slopes of bed voidage with gas velocity are changed at the transition velocities. Lee and Kim [11] have reported that a variation in the logarithmic slope of bed voidage with gas velocity can be utilized to determine the transition velocity to the turbulent flow regime in the bed.

In the present study, the values of index n in Eq. (4) in the turbulent flow regime are found to be 3.12, 2.56 and 3.30 for the C-1, C-2 and C-3 particles, respectively, which are similar to the value of 3.65-4.60 reported in the particulate fluidized beds [10]. This may indicate a homogeneous bed expansion in the turbulent flow regime of coarse particles.

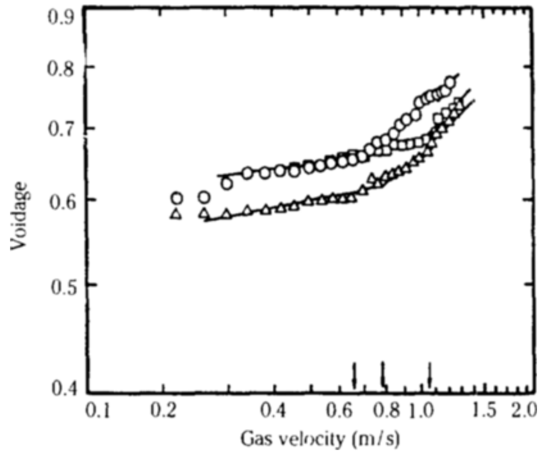

Fig. 8. Logarithmic plot of bed voidage with gas velocity.
○: C-1, △: C-2, □: C-3

In fine particle systems, the particles tend to gather in a cluster due to the particle agglomeration [12-14]. The modified Richardson-Zaki's equation has been used to reflect the cluster formation as bed expansion in the beds of fine particles as [14-17]:

$$\frac{U_g}{U_{ct}} = \epsilon^n \quad (5)$$

where U_{ct} is terminal velocity of clusters. A summary of the experimental conditions and the corresponding results on the index n of the present and pre-

Table 3. A summary of experimental conditions and results of the present and previous studies on the bed expansion in the slugging and turbulent flow regimes

Workers	D_t (m)	Particles	d_p (μm)	ρ_s (kg/m^3)	U_c/U_t	Slugging index n	turbulent index n
Massimilla [18]	0.156	catalyst	56	1000	3.1-4.2	11.7	
Carotenuto et al. [19]	0.152	FCC	60	940	2.0	8.0	5.6
Canada	0.61×0.61	glass	650	2480	0.51	3.4	1.85
et al. [8]	0.31×0.31		2600	2900	0.41	3.7	3.3
			2600	2900	0.48	2.71	3.3
Avidan and	0.152	catalyst	33	1670	23.40	46.0	14.0
Yerushalmi [17]		FCC	49	1070	7.84	9.2	5.0
		catalyst	49	1450	8.58	8.3	4.4
Abed [16]	0.152	FCC	54.8	850	5.20		4.16
Avidan et al. [20]	0.60	FCC	60	1220	1.03	8.5	4.30
Lee and Kim [11]	0.10	glass beads	362	2500	0.313	5.06	2.80
present study	0.10	coal	507	1407	0.22	12.3	3.12
			987		0.16	13.4	2.56
			1147		0.17	12.6	3.30

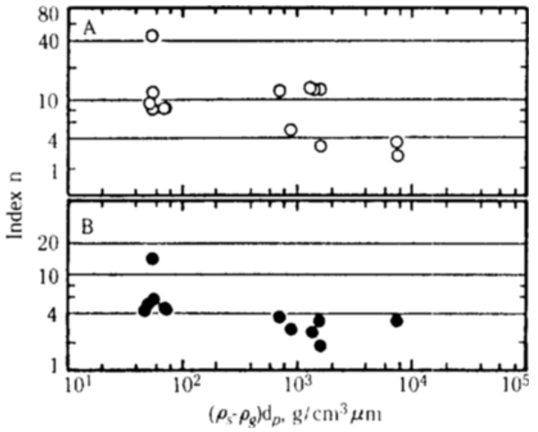

Fig. 9. Variations of index n with $(\rho_s-\rho_g)d_p$.
A: slugging, B: turbulent

vious studies is given in Table 3. As can be seen, the value of index n in the turbulent flow regime is smaller than that in the slugging flow regime. The smaller n value indicates a higher rate of bed expansion with an increase in gas velocity. This may be attributed to the greater bed homogeneity in the turbulent flow regime [11,17] due to the breakdown of large bubbles into small voids. Moreover, the index n decreases with increasing particle size and density (Fig. 9). This may be due to the increase of effective particle volume from the cluster formation in the bed of fine particles, which may result in a smaller bed expansion.

From the two-phase theory in fluidization [21], the gas flow in the bed divides into the interstitial gas flow through the emulsion phase at the minimum fluidizing state and the bubble flow. Using the two-phase theory, the bed expansion ratio, H/H_{mf}, in the slugging flow regime has been expressed as [22-24]:

$$\frac{H}{H_{mf}} = 1 + \frac{U_g - U_{mf}}{0.35\,(gD_t)^{1/2}} \quad \text{for axisymmetric slugs} \quad (6)$$

$$\frac{H}{H_{mf}} = 1 + \frac{U_g - U_{mf}}{0.35\,(2gD)^{1/2}} \quad \text{for asymmetric slugs} \quad (7)$$

Variations of the bed expansion in the present study and the predicted values from Eqs.(6) and (7) are shown in Fig. 10. As can be seen, the predictions of the two-phase theory largely overestimate the bed expansion in the slugging and turbulent flow regimes. Similarly, Satija and Fan [25] observed that the bed expansion from the two-phase theory is higher than the measured values in the slugging and turbulent flow regimes of coarse particles (1.0 - 6.96 mm). The deviation of bed expansion in the slugging flow regime from the two-phase theory may be due to the up and down movements of gas phase as the square-nosed slugs [26,27] as observed in the present study. In the turbulent flow regime, the slug breakdown and the rearrangement of small voids accompanying with swift acceleration may afford the higher interstitial gas velocity percolating through the dense phase [18,28]. Consequently, the larger deviation of bed expansion from the two-phase theory could be resulted. Therefore, the bed expansion in the slugging and turbulent flow regimes of coarse particles cannot be estimated from the two-phase theory.

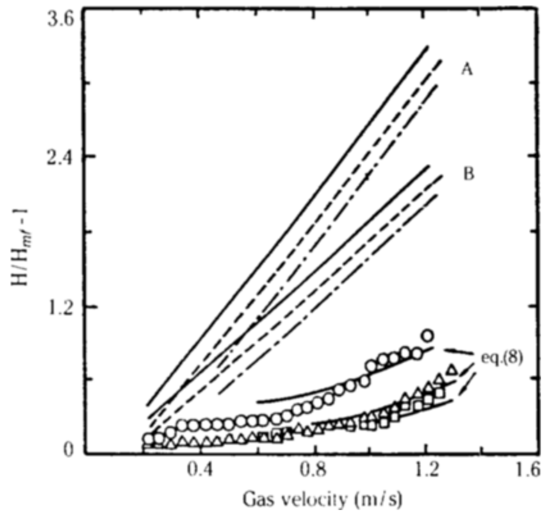

Fig. 10. Variation of bed expansion with gas velocity.
○: C-1, △: C-2, □: C-3
A: Eq.(6), B: Eq.(7)

In the present study, the bed expansion ratio in the turbulent flow regime of coal particles and glass beads [6,11] has been correlated as:

$$\frac{H}{H_{mf}} = 1 + 10.805\,Ar^{-0.290}\left(\frac{U_g - U_{mf}}{V_t}\right)^{0.635} \quad (8)$$

with a correlation coefficient of 0.90. A goodness of fit between the measured and calculated values from Eq. (8) can be seen in Fig. 10.

4. Prediction of transition velocity

The flow regime of turbulent fluidization was reported initially by Lanneau [29]. Recently, Lee and Kim [5] presented a correlation to predict the transition velocity in terms of the Reynolds number with the Archimedes number. However, the mechanism of slug breakdown into small voids at the transition region to the turbulent flow regime has not been well established until now.

As the gas velocity in the bed increases, slugs grow until they lose their stability, and consequent break down into small voids which remarks the transition to the turbulent flow regime. In the present study, it has assumed that the slug breakdown in the bed may be caused by the inertial force of a maximum stable slug which is exceeding the gravitational force of solids refluxing. Then, the criterion of the transition to the turbulent flow regime can be represented by:

$$Fr = \frac{\text{inertial force}}{\text{gravitational force}} = \frac{\rho_g U_{s,max}^2}{(\rho_s - \rho_g) g d_p} = 1 \quad (9)$$

where Fr is Froude number and $U_{s,max}$ is rise velocity of maximum stable slug. The $U_{s,mix}$ in Eq. (9) can be expressed as:

$$U_{s,max} = U_g - U_{mf} + 0.35 (g d_{s,max})^{1/2} \quad (10)$$

where $d_{s,max}$ is a maximum stable slug size in the slugging flow regime. Harrison et al. [30] proposed the following relation in the bed of coarse particles:

$$d_{s,max} = 1.32 \frac{\rho_s}{\rho_g} d_p \quad (11)$$

However, it has been found that Eq. (11) is valid even in the beds of fine particles [31]. Combining of Eq. (9) with Eqs.(10) and (11), the transition velocity to the turbulent flow regime can be predicted by:

$$U_c = \left[\frac{(\rho_s - \rho_g) g d_p}{\rho_g}\right]^{1/2} + U_{mf} - 0.402 \left(\frac{g \rho_s d_p}{\rho_g}\right)^{1/2} \quad (12)$$

Eq.(12) can be expressed in terms of the Reynolds and Archimedes numbers since the density of solid particles (ρ_s) is far greater than the gas density (ρ_g) as:

$$Re_c = 0.598 Ar^{1/2} + Re_{mf} \quad (13)$$

In Eq. (13), Re_{mf} can be predicted by the Wen-Yu equation[32] as:

$$Re_{mf} = [(33.7)^2 + 0.0408 Ar]^{1/2} - 33.7 \quad (14)$$

Then, the transition velocity to the turbulent flow regime in terms of the Reynolds number can be derived from Eqs.(13) and (14) as:

$$Re_c = [(33.7)^2 + 0.0408 Ar]^{1/2} - 0.598 Ar^{1/2} - 33.7 \quad (15)$$

with a correlation coefficient of 0.99 between the measured values of the present and previous studies [5,7-9,16,18-20,25,29,33-53] and calculated values from Eq.(15) as shown in Fig. 11. Therefore, this indicates that the transition to the turbulent flow regime is occurred by the instability of a maximum stable slug which comes from the inertial force exceeding the gravitational force of solid refluxing in the bed.

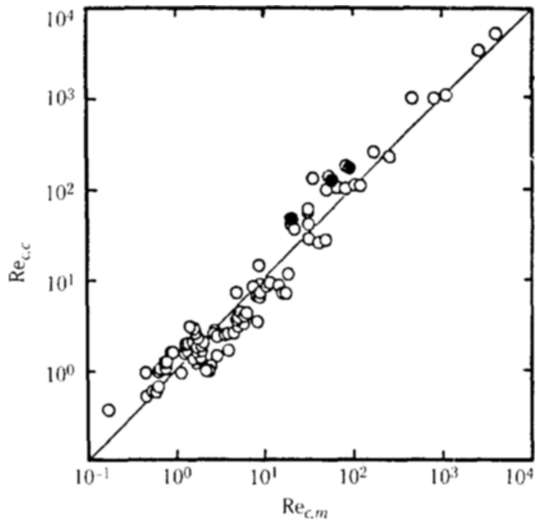

Fig. 11. Comparison of Reynolds number based on the transition velocity to the turbulent flow regime between the measured and calculated values.
● : present study

CONCLUSIONS

The transition velocity from the slugging to turbulent flow regimes can be determined from the mean amplitude, the standard deviation and the skewness of pressure fluctuations, the rise velocities of slugs and voids, and the bed voidage.

The voids rise velocity in the turbulent flow regime has been correlated with the relevant dimensionless parameters and operating variables.

The rate of bed expansion is more pronounced in the turbulent flow regime than that in the slugging flow regime with an increase in gas velocity. The bed expansion in the turbulent flow regime of coarse particles cannot be determined by the two-phase theory. The bed expansion ratio in the turbulent flow regime has been correlated with the dimensionless parameters.

The transition to the turbulent flow regime is mainly caused by the upflowing inertial force of a maximum stable slug exceeding the gravitational force of solid refluxing.

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NOMENCLATURE

Ar : Archimedes number, $d_p^3\rho_g(\rho_s-\rho_g)g/\mu^2$
d_p : mean particle size, m
d_{pi} : mean particle size in the i-th size interval, m
d_s : slug size, m
D_t : column diameter, m
Fr : Froude number, $\rho_g U_{s,max}^2/(\rho_s-\rho_g)gd_p$
g : gravitational constant m/s^2
H : expanded bed height, m
H_{mf} : bed height at minimum fluidizing condition, m
ΔL : distance between measuring points, m
n : Richardson-Zaki's index
ΔP : pressure drop, Pa
Re_c : Reynolds number based on the transition velocity to turbulent flow regime, $\rho_g d_p U_c/\mu$
Re_{mf} : Reynolds number based on the minimum fluidizing gas velocity, $\rho_g d_p U_{mf}/\mu$
U_c : transition velocity from slugging to turbulent flow regimes, m/s
U_{ct} : terminal velocity of clusters, m/s
U_g : superficial gas velocity, m/s
U_{mf} : minimum fluidizing gas velocity, m/s
U_s : slug rise velocity, m/s
U_t : terminal velocity of an individual particle, m/s
V_t : voids rise velocity, m/s
w_i : weight fraction of the i-th particle size

Greek Letters

ε : bed voidage
ε_{mf} : bed voidage at minimum fluidizing condition
μ : gas viscosity, Pa·s
ρ_g : gas density, kg/m^3
ρ_s : particle density, kg/m^3
σ : standard deviation of particle size distribution, m

Subscripts

av : average
c : calculated
m : measured
max : maximum stable bubble

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