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VOID CHARACTERISTICS IN TURBULENT FLUIDIZED BEDS

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Abstract—Void properties (size, rising velocity) in the turbulent flow regime have been determined in a 0.1 m-ID × 3.0 m high Plexiglas column of glass beads (d_p=0.362 mm) by using an optical fiber probe system.

The bubble size increases with an increase in gas velocity in the slugging flow regime but it sharply decreases in the turbulent flow regime. The mean amplitude of pressure fluctuations is linearly related to the bubble or void size in the bed. The void rising velocity is almost constant in the turbulent flow regime. Uniform condition of the bed structure in the turbulent flow regime can be determined from the void distribution coefficient in the bed. In addition, the bed condition in the turbulent flow regime has been evaluated from the variations of the void velocity coefficient and the propulsive power of a rising void with gas velocity.

INTRODUCTION

High velocity fluidization technology has been accepted as one of the promising means for the physical and chemical contacting processes due to the high contacting capability between gas and solid phases. In particular, the high velocity fluidized bed has played an important role in the commercial development of fossil fuels conversion techniques. However, in spite of its importance and wide applications, knowledge of the basic flow phenomena in the high velocity fluidized bed is still rudimentary. Moreover, fundamental research on the turbulent fluidized bed is relatively sparse.

In the bubbling and slugging fluidized beds, bubbles or slugs form, coalesce, and grow and move upwards in the bed. However, large bubbles or slugs are broken into small voids in the turbulent flow regime. Many investigators have observed the slug breakdown into small darting voids in the turbulent flow regime from visual observation [1], X-ray photographing [2], signals of capacitance probe [2-6], pressure fluctuations [7-11]. In particular, it has been reported that the slug breakdown in the turbulent flow regime is caused by the inertia force of a maximum stable slug which is exceeding the gravitational force of solid refluxing in the bed [12]. However, information on the void characteristics in the turbulent flow regime is still lacking. Therefore, in this study, void properties such as rise velocity and size of small voids in a turbulent fluidized bed have been studied with an optical fiber probe system. Also, bubble and void size has been related to the mean amplitude of pressure fluctuations in the bed. In addition, the bed condition in the turbulent flow regime has been evaluated from the variations of void parameters such as its distribution and the void velocity coefficient and the propulsive power of a rising void. To our knowledge, this is the first time to measure the void size and its rise velocity in the turbulent flow regime by the optical fiber probe system.

EXPERIMENTAL

Experiments were carried out in a 0.1 m-ID×3.0 m high Plexiglas column. The details of the experimental setup and the experimental procedures for measuring pressure fluctuations are described in previous publications [11, 13]. The column was initially loaded with 10 kg of glass beads (d_p=0.362 mm) giving static bed height of 1.0 m. The particles were supported on a bubble cap distributor plate which contained 7 bubble caps in which 6×3.0 mm in diameter holes were drilled around each bubble cap. The distributor was situated between the main column and a 0.1 m-ID×0.2 m high air box into which air was fed to the column

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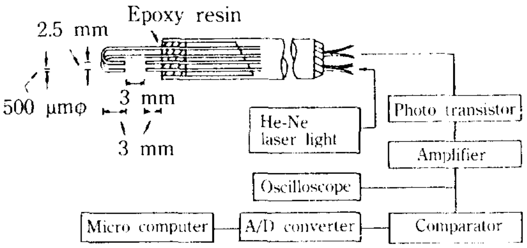

Fig. 1. Schematic diagram of the optical fiber probe system.

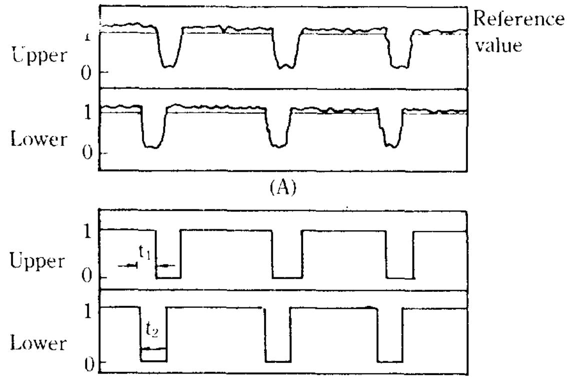

Fig. 2. Typical response signals in the lower and upper tips of optical fiber probe.

A: raw signal, B: smoothing signal by using comparator

through a pressure regulator, oil filter and a calibrated rotameter. The entrained solid particles from the bed were collected by the primary and secondary cyclones in series and were simultaneously recycled to the main bed. The minimum fluidizing gas velocity was found to be 0.105 m/s for the present particles.

The pressure fluctuations in the bed were measured by means of pressure transducers (Fisher Controls Co., 1151). The continuous pressure signal from the transducer was amplified and sent via an A/D converter to a personal computer (Apple IIe) for recording.

The mean amplitude of pressure fluctuations for N sample values can be obtained from:

$$\delta = \frac{1}{N} \sum_{n=1}^{N} | x_n - x | \quad (1)$$

where x_n is n-th pressure fluctuation data and x is the mean value of pressure fluctuations.

In the present study, an optical fiber probe system has been used to determine the bubble size and velocity in the bed. A schematic diagram of an optical fiber probe system is shown in Fig. 1. The optical fiber probe consists of two pairs of optical fibers with a diameter of 500 μm. One pair is a light projector from the light source of an Helium-Neon laser (2 mW, Japan Laser Co., JLH-RT20U), and the other at the opposite side was a receiver of the light transmitted across the probe spacing (3 mm) which was connected to two photo transistors (Kodenshi, Co., ST-KLBII). The tips of the optical fiber were cut vertically to the axis of the fiber and the fibers were supported with needles of 0.5 mm hole diameter and fixed with epoxy resin in a stainless steel pipe of 7.8 mm-ID and 0.20 m length. The upper and lower probes are apart 2.5 mm. The length from the tip of the optical fiber to the light source or the detector is about 1.0 m. The optical fiber probe is horizontally located at a level of 0.53 m above the distributor and it can be moved radially across the bed width through a pressure tap hole. The good reproducibility of bubble or void property data can be obtained above the bed level of 0.13 m from the distributor in the given ranges of gas velocity employed in this study.

The received light intensity was converted into an electric signal by a photo transistor. The magnitude of the signal depends on the intensity of transmitted light from the projector to the receiver of the optical fiber probe. The output signal from the photo transistor had a high voltage when the clusters of solids passed the probe spacing because of the weak light intensity into the photo transistor, and had a low voltage when a bubble or void passes the probe tip since the light passed from the light projector to receiver of the optical fiber probe. The output signal of the photo transistor was amplified, monitored by a oscilloscope, and sent via a comparator and A/D converter to a micro computer (IBM/XT) for recording. The sampling interval of the signals was selected at 500 μs and 180,000 samples were collected during the sampling time of 90 s for each experimental conditions.

Typical response signals in the lower and upper tips of the optical fiber probe are shown in Fig. 2. The frequency of fluctuation signals from the optical fiber probe is much greater than that of the fluctuation of bubbles in the bed due to the movement of dispersed solid particles around the probe. Therefore, in the present study, a smooth output signal was obtained with the aid of an oscilloscope and a comparator. The comparator circuit was designed to produce a signal more suitable for the automatic processing in the form of rectangular pulses of a constant height (Fig. 2B). A bubble or void generates an electric impulse with time. The duration time of such a rectangular impulse

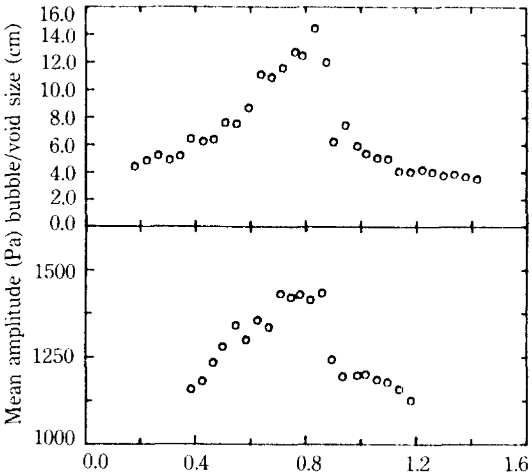

Fig. 3. The effect of gas velocity on bubble/void size and the mean amplitude of pressure fluctuations.

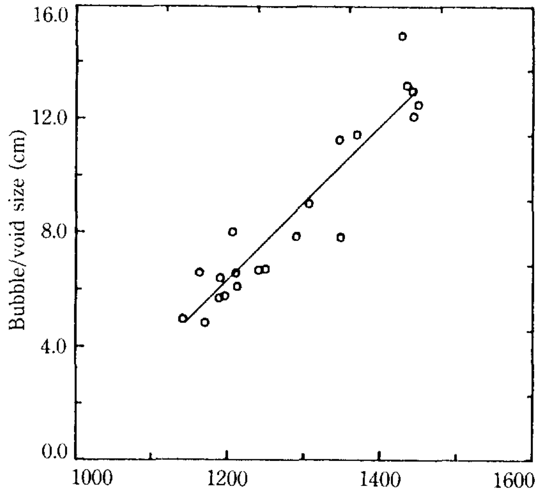

Fig. 4. Variation of bubble/void size with the mean amplitude of pressure fluctuations.

was identical to the bubble or void passing time at the probe location. The output voltage was calibrated with a variable resistor in the comparator circuit by putting the probe in a quiescent bed of solid particles (1.0 V) and atmosphere (0.0 V).

Then, the bubble or void rise velocity can be calculated from:

$$U_b = \frac{1}{N_b} \sum_{i=1}^{N_b} \frac{l}{t_{1i}} \tag{2}$$

where l is the distance between the lower and upper tips of the optical fiber probe, N_b is the number of bubbles or voids detecting at the probe during the sampling time, and t_{1i} is time lag between the two probes.

Also, the bubble or void chord length can be calculated from:

$$l_b = \frac{1}{N_b} \sum_{i=1}^{N_b} U_{bi} t_{2i} \tag{3}$$

where t_{2i} is the time duration of an electric impulse.

The obtained bubble length was transformed into bubble diameter from the relation of Rowe and Masson [14] as:

$$d_b = 1.63\ l_b. \tag{4}$$

RESULTS AND DISCUSSION

The transition velocity from the slugging to turbulent flow regimes in the bed of present particle has been found to be 0.85 m/s in previous studies [11, 13].

The effect of gas velocity on bubble/void size and mean amplitude of pressure fluctuations at 0.53 m above the distributor plate are shown in Fig. 3. As can be seen, the bubble or void size increase with an increase in gas velocity which causes the increase of the mean amplitude of pressure fluctuations to a maximum value at a gas velocity, and thereafter, it sharply reduces in the turbulent flow regime. The gas velocity at which a maximum bubble size attained is very similar to the transition gas velocity to the turbulent flow regime. The decrease of bubble size with increasing gas velocity can be attributed to the breakdown of large bubbles into small voids in the turbulent flow regime which results in a decrease in the mean amplitude of pressure fluctuations in the bed. This slug breakdown to small bubbles or voids provides the increase of gas-solids mixing in the turbulent fluidized beds [9, 15, 16]. In particular, the variation of bubble size is similar to that of the mean amplitude of pressure fluctuations with gas velocity.

For a single bubble rising in a fluidized bed, pressure at the pressure tip gradually increases during the rise of a single bubble and the pressure exhibits a maximum value when the roof of bubble touches the pressure tip. The pressure fluctuation begins to decrease its lowest value when the bubble bottom region reaches the pressure tip. Consequently, the pressure fluctuations in the bed are mainly caused by the successive rising of bubbles or voids and the mean amplitude of pressure fluctuations in the bed increases linearly with an increase in bubble or void size (Fig. 4). Therefore, the variation of the mean ampli-

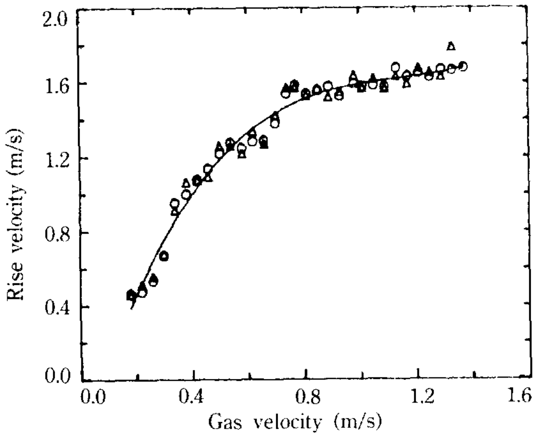

Fig. 5. The effect of gas velocity on bubble/void rise velocity.

○: present study, △: pressure waveform velocity [13]

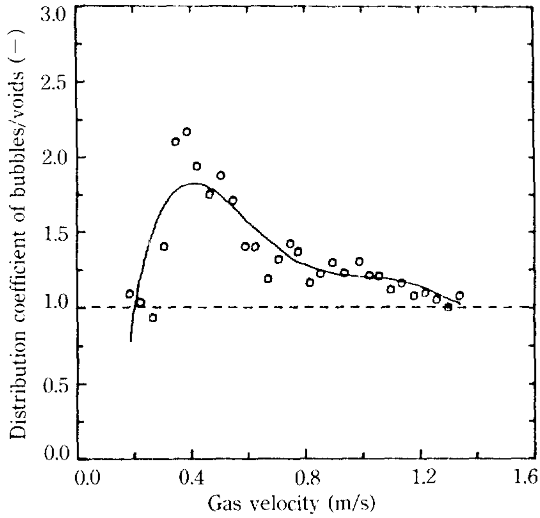

Fig. 6. The effect of gas velocity on the distribution coefficient of bubbles/voids.

tude of pressure fluctuations is due to the variation of bubble or void size in the bed.

The effect of gas velocity on bubble/void rising velocity is shown in Fig. 5, in which the bubble/void rise velocity is compared to the rise velocity of pressure waveform reported in a previous study [13]. As can be seen, the bubble or void rise velocity is very similar to the rise velocity of pressure waveform in the bed. Also, the bubble rise velocity increases with increasing gas velocity up to the transition velocity to the turbulent flow regime, thereafter, it remains almost constant with an increase in gas velocity in the turbulent flow regime. This may be attributed to the higher interstitial gas velocity through the particulate phase which is formed by the breakdown of large slugs into small voids in the turbulent flow regime [12, 13]. Therefore, it has been reported that the onset point of the almost constant bubble rise velocity can be regarded as the onset point to the turbulent flow regime in the bed [13, 17].

For freely bubbling fluidized beds, the bubble rising velocity is commonly represented as [18,19]:

$$U_b = (U_g - U_{mf}) + U_{b\infty} \tag{5}$$

where $U_{b\infty}$ is rising velocity of an isolated bubble defined as $0.71\sqrt{gd_b}$.

In practice, the bubble velocity in freely bubbling fluidized beds is influenced by the motion of other vicinity bubbles and by the size and radial distribution of bubbles. Then, the bubble velocity has been expressed as [20-22]:

$$U_b = C_o(U_g - U_{mf}) + U_{b\infty} \tag{6}$$

where C_o is the distribution coefficient which depends on the radial distribution of bubbles in the bed.

The distribution coefficient represents the degree of radial bubble distribution; the uniform radial distribution has $C_o = 1$, the skewed bubble distribution near the outer wall has $C_o < 1$, and the distribution concentrated at the axis of the column has $C_o > 1$.

The distribution coefficient of bubbles or voids (C_o) in Eq. (6) can be determined from the measured bubble/void size and velocity. The variation of the distribution coefficient with increasing gas velocity is shown in Fig. 6. As can be seen, C_o values are found to be near to unity at lower gas velocities, and C_o values are higher than unity in the slugging flow regime. The square-nosed slugs have been observed in the beds of coarse particles as used in the present study. Therefore, the bubbles are concentrated at the axis of the column in the slugging flow regime which may result in higher C_o values. However, C_o value is approaching to unity with an increase in gas velocity in the turbulent flow regime. This may be due to the breakdown of large bubbles into small bubbles or voids which contributes the homogeneous bed structure in the turbulent flow regime. In particular, the average values of C_o over the entire bed of bubbling flow regime are found to be in the range 1.3-1.4 [23], which is similar to the value of the turbulent flow regime in present study. Therefore, it may be concluded that the bed condition in the turbulent flow regime is similar to that in the freely bubbling flow regime.

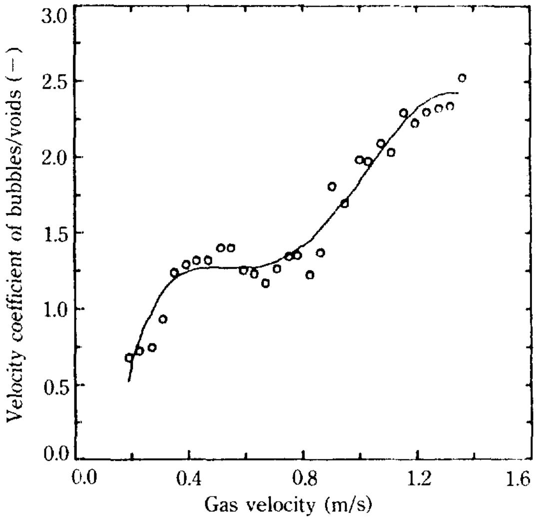

Fig. 7. The effect of gas velocity on the velocity coefficient of bubbles/voids.

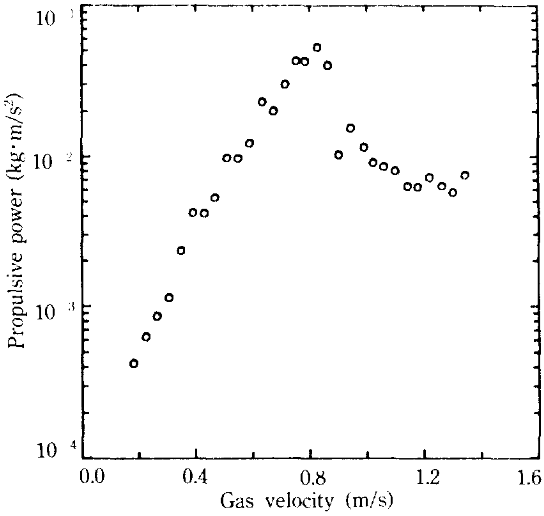

Fig. 8. The effect of gas velocity on the propulsive power of a rising bubble/void.

The velocity coefficient of bubbles or voids has been defined as [24]:

$$C_v = U_b/\sqrt{g d_b}\,. \tag{7}$$

This information provides the rising behavior between the multi-bubbles and an isolated bubble.

The effect of gas velocity on C_v is shown in Fig. 7. At lower velocities, C_v is approximately equal to 0.71, which may indicate that the bubble rise velocity in the lower gas velocities is similar to that of an isolated bubble in the bed. However, C_v is higher at higher gas velocities due to the accelerated bubble rising velocity which is caused by the bubble coalescence in the bed. In addition, C_v is almost constant in the slugging flow regime since the up and down movements of gas phase through the particulate and the square-nosed slug phases [25]. Also, C_v increases remarkably with increasing gas velocity in the turbulent flow regime which may be attributed to the acceleration of small darting voids from the breakdown of large bubbles in the turbulent flow regime. This larger velocities of small voids may provide the increase of solid mixing in the turbulent flow regime due to the rapid up and down movements of solid particles in the bed [16]. In addition, the velocity coefficient is changed appreciably at the transition region to the turbulent flow regime as can be seen in Fig. 7.

The propulsive power of a rising bubble (F_p) in the bed can be defined as:

$$F_p = \frac{\pi}{4}\rho_g U_b^2 d_b^2 \tag{8}$$

The variation of F_p with an increase in gas velocity is shown in Fig. 8. As can be seen, F_p increases with increasing gas velocity due to the increasing bubble size and rising velocity. However, F_p sharply decreases with an increase in gas velocity in the turbulent flow regime. The slug breakdown into small voids in the turbulent flow regime affords the decrease of F_p due to the decrease of the bubble/void size (Fig. 4). Also, the rearrangement of small voids from the slug breakdown in the turbulent flow regime results in high interstitial gas velocity percolating through the dense phase in the bed [15]. Therefore, the gas flow in the turbulent flow regime may provide an increase in the propulsive power of gas percolating through the interstices of the dense phase in the bed. This may provide the decrease of the propulsive power of a rising void in the turbulent flow regime. Moreover, the gravitational force of solid refluxing in the turbulent flow regime may affect the decrease of the propulsive power of a rising void.

CONCLUSIONS

The bubble size increases with an increase in gas velocity in the slugging flow regime, it goes through a maximum value (0.15 m), and thereafter, it sharply decreases with an increase in gas velocity in the turbulent flow regime. The mean amplitude of pressure fluctuations is directly proportional to the bubble/void size in the bed. The rise velocity of voids (1.6-1.7 m/s) is almost constant in the turbulent flow regime. Uniform bed structure in the turbulent flow regime has been evaluated from the distribution and velocity coefficients of voids in the bed. The propulsive power of a rising void sharply reduces in the turbulent flow regime.

ACKNOWLEDGEMENT

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NOMENCLATURE

C_o : distribution constant of bubble/void across the bed [-]
C_v : velocity coefficient of bubble/void defined in Eq.(6) [-]
d_b : equivalent bubble diameter [m]
d_p : particle size [m]
F_p : propulsive power of a rising bubble/void [kg·m/s^2]
g : gravitational constant [m/s^2]
l : distance between the lower and upper tips of optical fiber probe [m]
l_b : bubble or void length [m]
N : number of samples [-]
N_b : number of bubbles/voids [-]
t_1 : time lag between two probes [s]
t_2 : duration time of an electric impulse [s]
U_b : bubble/void rise velocity [m/s]
$U_{b\infty}$: rise velocity of an isolated bubble or void [m/s]
U_g : superficial gas velocity [m/s]
U_{mf} : minimum fluidizing velocity [m/s]
$\bar{x}$: mean value of pressure fluctuations [Pa]
x_n : n-th variables of pressure fluctuations data [Pa]

Greek Letters

δ : mean amplitude of pressure fluctuations [Pa]
ρ_g : gas density [kg/m^3]

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