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RISE VELOCITIES OF SLUGS AND VOIDS IN SLUGGING AND TURBULENT FLUIDIZED BEDS

Geun Seong LEE and Sang Done KIM*

Department of Chemical Engineering, Korea Advanced Institute of Science and Technology, Seoul 130-650, Korea

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Abstract—Using the cross-correlation function of two pressure fluctuation signals, the rise velocities of slugs and voids and the slug frequency in the slugging and turbulent fluidized beds of glass beads($\bar{d}_p$= 0.362 mm) have been determined in a 0.1 m-ID × 3.0 m high Plexiglas column.

The slug rise velocity in the slugging flow regime increases with an increase in gas velocity, while the void velocity remains almost constant with the variation of gas velocity in the turbulent flow regime. The slug frequencies are found to be insensitive to the increase of gas velocity in the slugging flow regime within the frequency range of 0.47-0.64 Hz.

The data of the present and previous studies on the slug rise velocity in the slugging flow regime have been correlated as

$$U_s=1.73\times 10^{-2}\left(\frac{\bar{d}_p}{D_t}\right)^{0.093}\left(\frac{\rho_s}{\rho_g}\right)^{-0.616}(U_g-U_{mf})+0.35(gD_t)^{1/2}$$

INTRODUCTION

In a bubbling fluidized bed, as gas velocity is increased, the bubbles grow considerably in size as a result of coalescence. The phenomenon may be observed in which each of bubbles appears to occupy the whole cross section of the bed, which marks the slugging flow regime in a fluidized bed. A further increase of gas velocity gives the turbulent flow regime which is characterized by the breakdown of larger slugs into smaller ones[1-3].

In recent years, considerable interest has been shown in the high velocity fluidized bed beyond the bubbling flow regime. Though the operation in the slugging flow regime produces large pressure fluctuations, the slugging fluidized bed is easy to scale-up. The turbulent fluidized bed has the great contacting capability between the gas and solid phases without bubble formation in the catalytic and non-catalytic reaction systems. Especially, a knowledge of the rise velocity of slugs or voids in the slugging and turbulent flow regimes is important since it governs the gas residence time in a fluidized bed which is one of the main factors determining the rate of mass and heat transfers between the dilute and dense phases.

For slugging fluidized beds, the rise velocity of slugs has been measured by the several investigators (Table 1). It has been found that a slug velocity of coarse particle beds is lower than that of fine particle beds[10,12]. However, it has not been suggested the generalized equation involved the properties of particles for slug rise velocity in the slugging flow regime.

Also, slug rise velocity in the transition region from the slugging to the turbulent flow regimes has been studied by previous investigators[6,13]. By contrast, studies on the rise velocity of the smaller bubbles or voids from the breakdown of slugs in the turbulent flow regime are relatively sparse.

Therefore, in this study, the rise velocities of slugs and small voids in the slugging and the turbulent flow regimes have been determined from the cross-correlation function between two pressure fluctuation signals. Also, the slug frequency has been examined by calculating the power spectral density function of the pressure fluctuations. The obtained results and the data from the literature have been used to develop a generalized slug rise velocity equation for the slugging flow regime.

CROSS-CORRELATION FUNCTION

The cross-correlation function between two continuous, stationary and ergodic random variables, X(t) and Y(t), is expressed as[9,14]

$$\phi_{xy}=\lim_{T\to\infty}\frac{1}{T}\int_{-T/2}^{T/2}x(t)y(t+\tau)dt \qquad (1)$$

*To whom all correspondence should be addressed.

Table 1. Summary of measurements of slug rise velocity in the fluidized beds

Workers	Bed diameter (cm)	Particles	Mean diameter (μm)	Particle density (g/cm^3)	U_g/U_{mf}	Experimental methods	Given relation
Lanneau (1960)	7.6	Catalyst	70	2.0	5-76	C	$U_s=(U_g-U_{mf})+0.41(gD_t)^{1/2}$
Ormiston et al. (1965)	2.5 5.7 14.0	Catalyst	41.5		1.03-2.5	C, X	$U_s=(0.87\text{-}9.68)(U_g-U_{mf})$ $+(0.335\text{-}0.383)(gD_t)^{1/2}$
Matsen et al. (1969)	46.0	Sand	125.0				$U_s=(U_g-U_{mf})+0.35(gD_t)^{1/2}$
Kehoe and Davidson (1971)	2.54 5.10 10.2	Quartz Catalyst Sand	68-275 55, 62 145	2.55-2.83 1.1 2.65	1.34-135.0 2.10-85.5 2.77-13.0	C,X	$U_s=(U_g-U_{mf})+0.35(gD_t)^{1/2}$
Carotenuto et al. (1974)	15.0	FCC Alumina	60 95 270	0.94 1.55	1.0-2.91	C	$U_s=(U_g-U_{mf})+0.35(gD_t)^{1/2}$ $U_s=(U_g-U_{mf})+0.35(2gD_t)^{1/2}$
Thiel and Potter (1977)	5.1 10.2 21.8	FCC+Al Glass spheroid	58.6 74.7	1.73 2.45	4.76-133	C	$U_s=(U_g-U_{mf})+0.35(gD_t)^{1/2}$
Fan et al. (1983)	10.2 15.3 20.3	Sand	491 711 1122	2.62 2.64 2.65	1.2-3.5	P	$U_s=2.43(\frac{\bar{d}_p}{D_t})^{-0.5}(\frac{\rho_s}{1000\rho_g})^{-4.2}$ $(U_g-U_{mf})+0.35(gD_t)^{1/2}$
Satija and Fan(1985)	10.2	Glass beads Aluminum	1000 2320 5500 6900	2.77 3.537	0.2-1.5* 1.4-1.5* 0.5-1.5*	P	$U_s=1.48(\frac{\bar{d}_p}{D_t})^{-0.9}(\frac{\rho_s}{1000\rho_g})^{-4.2}$ $(U_g-U_{mf})+0.35(gD_t)^{1/2}$
Cui et al. (1985)	15.0	Silica gel	650		2.3-11.8	O	$U_s=0.7613(U_g-U_{mf})$ $+0.35(1.19gD_t)^{1/2}$

C: Capacitance probe, O: Optical fiber, P: Pressure transducer, X: X-ray, *: U_g-U_{mf} value (m/s)

where x(t) is the value of X(t) sampled at time t, and $y(t+\tau)$ is the value of Y(t) sampled at time $t+\tau$. In this work, X(t) and Y(t) are pressure fluctuation signals at an upstream and a downstream in the bed, respectively. The average time required for a pressure fluctuation waveform to travel between these two points is the transit time, τ_m, at which the cross-correlation function between the two detected pressure fluctuation signals is maximum[9,15].

The velocity of the pressure fluctuation waveform, V_f, can be calculated from

$$V_f=\frac{L}{\tau_m} \qquad (2)$$

where L is the known distance between the two measuring locations in the bed.

The velocity of a pressure fluctuation waveform defined in Eq.(2) is the average rise velocity of slugs or voids in each flow regime;

$$U_s=V_f$$
$$V_t=V_f \qquad (3)$$

where U_s and V_t are the rise velocities of slugs and smaller voids in the slugging and the turbulent flow regimes, respectively.

EXPERIMENTAL

Experiments were carried out in a Plexiglas column of 0.1m-ID×3 m high as shown schematically in Fig. 1. Glass beads with a mean diameter of 0.362 mm (0.210-0.417 mm) and density of 2500 kg/m^3 were

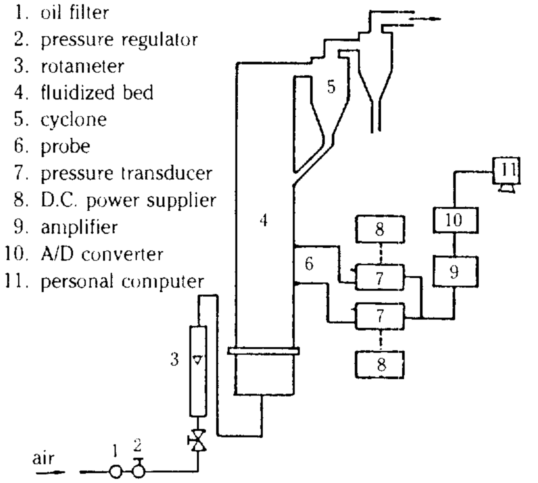

Fig. 1. Schematic diagram of experimental apparatus.

fluidized by compressed air. The minimum fluidizing velocity of the particle was found to be 0.105 m/s. The solid particles were supported on a bubble cap distributor plate which contained 7 bubble caps in which 6×3.0mm in diameter holes were drilled around each bubble cap. The distributor was situated between the main column and the air box into which air was fed to the column through a pressure regulator, oil filter and a calibrated rotameter. The entrained solid particles from the bed were collected by the first and second cyclones in series and they were recycled to the main bed simultaneously. The column was initially loaded with 10 kg of glass beads giving static bed height of 1m. The pressure probe was made of 0.78 cm-ID stainless steel pipe which can be moved radially across the bed width through the pressure tap hole. One end of the probe was covered with a 200 mesh size screen to prevent the solid particles from the bed and the other end was connected to a differential pressure transducer (Fisher Controls Co., 1151). The pressure transducer was connected to a D.C. power supplier which has two input channels and the output voltages were calibrated against the pressure difference between two channels in the linear response range of 0.0-6.14 kPa. For measuring pressure fluctuations, one channel of the transducer was connected to the pressure probe in the bed and the other one was exposed to the atmosphere. In order to determine the effect of bed height on the rise velocities of slugs or voids, the velocities were measured along the bed height above the distributor. The measured velocities are found to decrease with bed height up to 23 cm above the distributor and they remained almost constant above the bed level of 23 cm from the distributor in the given ranges of gas velocity employed in this study.

In general, the correlation between the two measured signals becomes smaller and it is difficult to locate the peak of the cross-correlation function with an increase in the distance. On the contrary, the directional characteristics of the signals become less distinct and the error caused by digitizing the signals to compute the transit time becomes larger with a decrease in the distance [16]. It has been shown that a distance between the two vertically separated pressure taps approximately equal to or two times larger than a diameter of the column is a suitable choice to measure bubble rising velocity in fluidized beds[9]. Therefore, the measuring points were selected at 33 and 53cm above the distributor throughout this study.

The continuous pressure signals from the transducer were amplified and sent them via an A/D converter to a personal computer (Apple IIe) for the record. The sampling interval of the fluctuation was selected at 10 ms and 8192 samples were collected for each experimental condition. The cross-correlation function between the two fluctuation signals was determined by off-line calculation with Eq. (1). The time shift, τ_m, was determined where the cross-correlation function is maximum, and the average rise velocity of slugs and voids in the slugging and turbulent flow regimes was determined from Eqs. (2) and (3), respectively.

In analyzing the pressure fluctuation signals with respect to the dominant frequency, an estimated smooth power spectral density function was obtained by the Hanning Window function[17] procedure.

RESULTS AND DISCUSSION

In order to operate a fluidized bed in the slugging flow regime, the onset gas velocity to the slugging flow regime in the bed was determined based on the following equations from previous studies[18-20];

$$\frac{U_{ms}-U_{mf}}{0.35(gD_t)^{1/2}}=0.2 \tag{4}$$

$$\frac{\rho_s U_{ms}^{2}}{g(\rho_s-\rho_g)\bar{d}_p}=51.4\left(\frac{D_t}{H_{se}}\right)^{1.79}\left(\frac{\rho_s}{\rho_g}\right)^{0.09} + 0.00416\left[\frac{\bar{d}_p^3\rho_s g(\rho_s-\rho_g)}{\mu^2}\right] \tag{5}$$

$$150\left[\frac{(1-\epsilon_{mf})^2\mu}{\epsilon_{mf}^3(\phi_s\bar{d}_p)^2}(U_{ms}-U_{mf})\right]+1.75\left[\frac{(1-\epsilon_{mf})\rho_g}{\epsilon_{mf}^3(\phi_s\bar{d}_p)}(U_{ms}^2-2U_{mf}^2)\right]=0 \tag{6}$$

The onset gas velocities to slugging flow regime calculated from the above three equations are 0.17, 0.11 and 0.19 m/s, respectively. Therefore, the employed

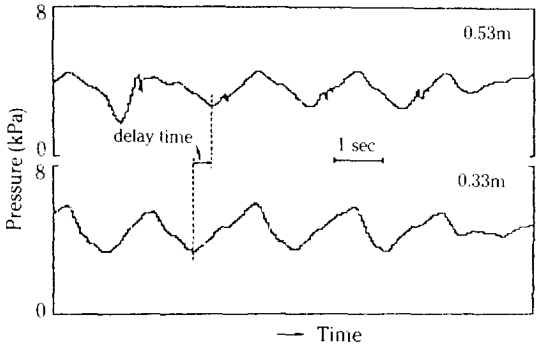

Fig. 2. Pressure fluctuation signals at a gas velocity of 0.42m/s.

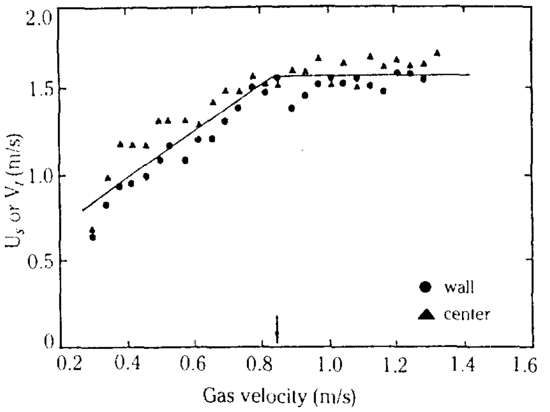

Fig. 4. Variation of the rise velocity of smaller bubbles or voids with gas velocity.

gas velocity in this study was 0.30 m/s which is higher than the values from the above equations since the slug flow was observed at a gas velocity of 0.30 m/s. In the slugging flow regime, three types of slugs have been observed, namely, axisymmetric, asymmetric and square-nosed slugs[12,21,22]. In general, the square-nosed slug can be observed in the bed of coarse particles as used in the present study.

Typical pressure fluctuation signals obtained at a gas velocity of 0.42 m/s, taken simultaneously from the two pressure taps, are shown in Fig. 2. The figure shows that the two curves do not coincide and the upper curve lags behind the lower ones. The lag or delay time is considered the travelling time of smaller bubbles or slugs from the lower to the upper taps.

The calculated typical cross-correlation functions are shown in Fig. 3. The average time required for a pressure fluctuation signal to travel the two locations of the bed is the transit time where the cross-correlation function is maximum

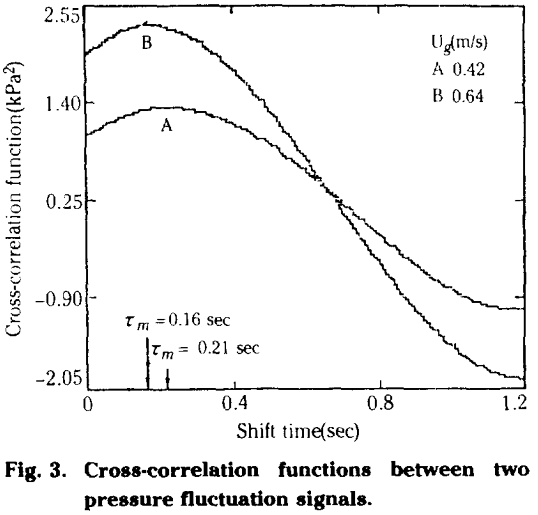

Fig. 3. Cross-correlation functions between two pressure fluctuation signals.

The variation of the rise velocity calculated from the cross-correlation function with an increase in gas velocity are shown in Fig. 4. As can be seen, the rise velocity increases with gas velocity up to around 0.85 m/s, thereafter, it remains almost constant with an increase in gas velocity. From the previous studies, the change of slope in the rise velocity of smaller bubbles or voids with gas velocity in the turbulent flow regime of fine particles was higher than that in the slugging flow regime[6] but, a reverse trend was reported by Crescitelli et al. [13]. However, in the bed of coarse particles, the rise velocity of voids in the turbulent flow regime has found to be almost constant with the variation of gas velocity in the present and previous studies[9]. The nearly constant rise velocity is observed beyond a certain gas velocity which can be attributed to the breakdown of slugs into smaller bubbles or voids. The onset point of the constant rise velocity of voids can be regarded as the onset to the turbulent flow regime in the bed. Carotenuto et al.[7] observed that many small bubbles or voids rise regularly at relatively low velocity in the turbulent flow regime than the slugs in the slugging flow regime. Thus, it can be expressed as the rise velocity of smaller bubbles or voids in the turbulent flow regime by the following equation.

$$V_t = V_{mt} \tag{7}$$

The determined transition velocity from the slugging to the turbulent flow regimes from the rise velocity of smaller bubbles or voids in Fig. 4 is quite similar to the values from the statistical properties of pressure fluctuations[23]. It may imply that the transition velocity from the slugging to the turbulent flow regimes can be determined from the rise velocity of smaller bubbles or voids. As can be seen in the figure, the rise velocity in the center is somewhat higher than that in the wall of the column in the given range of gas velocity employed in this study. It may be due to the friction between the smaller bubbles or voids and the wall of the bed and the downward motion of solid particles along the wall of the bed which will reduce the rise velocity of smaller bubbles[9,12].

Slug rise velocity has been measured and correlated by several investigators as shown in Table 1. In general, the slug rise velocity has been correlated by the following equation which is similar to the behavior of slugs in the gas-liquid system[4,12,24].

$$U_s = k(U_g - U_{mf}) + U_{is} \tag{8}$$

where $U_{is} = K(gD_t)^{1/2}$, $K = 0.35$

In the previous studies[12,18,22], the constant K value in Eq.(8) is found to be 0.5 for asymmetric slugs instead of 0.35 for an isolated slug. Rearranging Eq.(8) gives the following equation;

$$U_s - U_{is} = k(U_g - U_{mf}) \tag{9}$$

The variation of $(U_s\text{-}U_{is})$ with $(U_g\text{-}U_{mf})$ is shown in Fig. 5 with the data of previous[1,4,6-9] and the present studies. As can be seen from the figure, the values of k are wide spread according to the equipment size and the properties of particles in the range of 0.2-12.5. Therefore, the effects of equipment size and properties

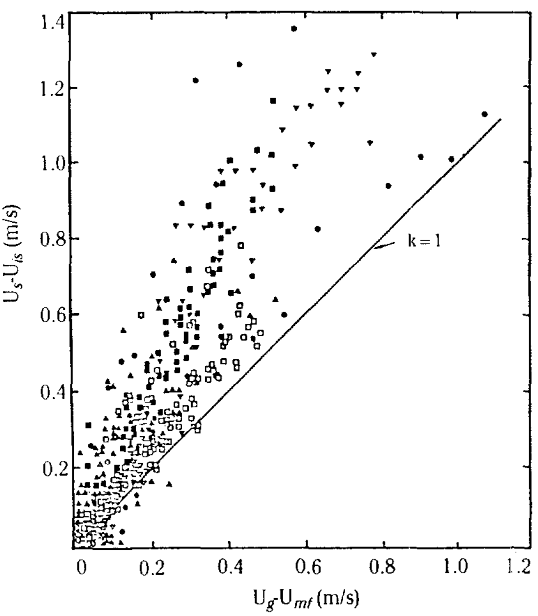

Fig. 5. Variation of $(U_s\text{-}U_{is})$ with $(U_g\text{-}U_{mf})$.

○: Ormiston et al.[4] △: Lanneau[1]
□: Kehoe and Davidson [6] ▽: Hovmand et al.[25]
●: Carotenuto et al.[7] ▲: Thiel and Potter[8]
■: Fan et al.[9] ▼: This study

of particles on the rise velocity of slugs in Eq.(8) have to be considered. Consequently, an attempt is made to correlate the value of k in Eq.(8) for the slug rise velocity with the data of other studies[1,4,6-9] by an expression similar to that proposed by Fan et al.[9]. The correlation is

$$U_s = 1.73\times10^{-2}\left(\frac{\bar{d}_p}{D_t}\right)^{-0.093}\left(\frac{\rho_s}{\rho_g}\right)^{-0.616}(U_g - U_{mf}) + 0.35(gD_t)^{1/2} \tag{10}$$

with a correlation coefficient of 0.89. This correlation covers the ranges of variables $2.69\times10^{-4} \leq \bar{d}_p/D_t \leq 9.92\times10^{-3}$ and $793.9 \leq \rho_s/\rho_g \leq 2390.2$. As can be seen in Eq. (10), the slugs rise faster with the decrease of particle density and the ratio of particle size to bed diameter at a given gas velocity. For the bed of coarse particles, the gas phase moves up and down freely from the particulate to the slug phases[9] and the upward movement of the slugs is largely influenced by raining of solid particles through the slugs[12].

The goodness of fit between the measured and calculated values of the slug rise velocity from Eq.(10) is shown in Fig. 6. For the sake of comparison, the experimental data set used in Eq.(10) has been examined with the correlations of previous studies[9,10] as shown in Fig. 7. As can be seen in Figs. 6 and 7, the agreement between the values from the correlation of the present study and the experimental values is better than those of previous studies.

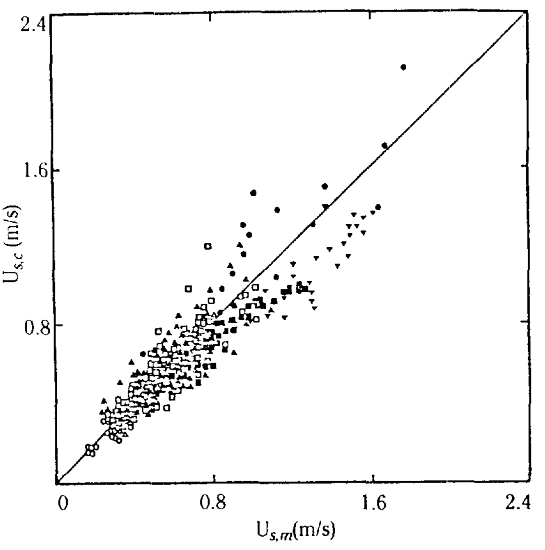

Fig. 6. Comparison between the measured and calculated values of the slug rise velocity in the slugging flow regime.

The symbols are identical as in Fig. 5.

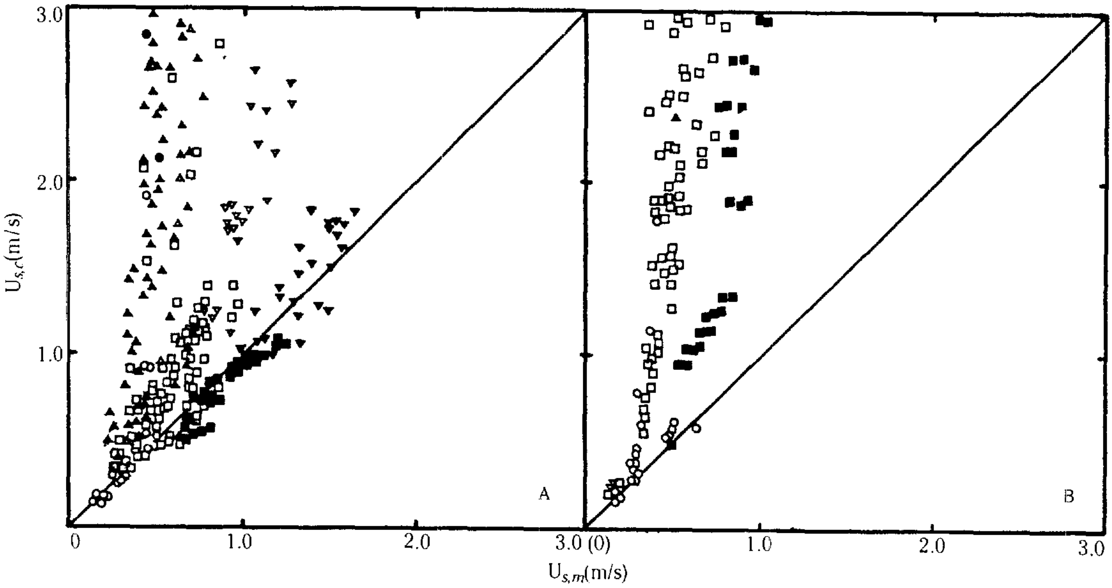

Fig. 7. Comparisons of the slug rise velocity between the measured and calculated values from the correlation of (A) Fan et al.[9] and (B) Satija and Fan[10].
The symbols are identical as in Fig. 5.

The obtained power spectral density function of pressure fluctuation signals at 0.53m above the distributor at a gas velocity of 0.71m/s is shown in Fig. 8. The dominant frequency of a pressure fluctuation signal can be determined from a peak of its power spectral density function of 0.63Hz as can be seen in the figure. The dominant frequency of the signals thus obtained is defined as the slug frequency in this study. The measured slug frequencies are found to be insensitive to an increase in gas velocity in the slugging flow regime within the frequency range of 0.47-0.64Hz. A similar tendency has been observed by Baeyens and Geldart[21], and Broadhurst and Becker[26] for the slug frequency to attain a limiting value which is not

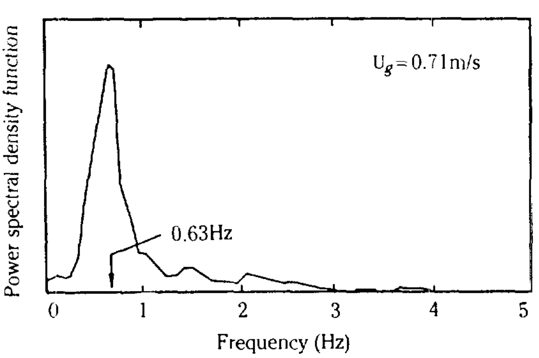

Fig. 8. Power spectral density function of pressure signals obtained at 0.53m above the distributor with a gas velocity of 0.71m/s.

influenced greatly by the particle properties and gas velocity above a certain value in the slugging flow regime. They proposed different correlations on the slug frequency as shown below.

$$f_s = 1.17 D_t^{-0.143} \tag{11}$$

$$f_s = 0.34 \left(\frac{D_t}{H_{mf}}\right)^{0.85} \left(\frac{g}{D_t}\right)^{0.5} \tag{12}$$

in which D_t is in cm. The calculated slug frequencies from Eqs. (11) and (12) for the present study are 0.84 and 0.48Hz, respectively. These values are quite similar to the values of the present study.

The rise velocity of smaller bubbles or voids in the turbulent flow regime is found to be about 1.62m/s in the present study as can be seen in Fig. 4 and it can be expressed by Eq.(7). The nearly constant rise velocity of smaller bubbles or voids regardless of the increase in gas velocity may be attributed to the higher interstitial gas velocity through the homogeneous particulate phase which is formed by the breakdown of large slugs into smaller bubbles or voids in the turbulent fluidized beds. Fan et al.[9] have measured the average rise velocity of pressure wave in the turbulent flow regime for the coarse particles which has been regarded as the rise velocity of smaller bubbles or voids in this study. They found that the average rise velocity decreases with an increase in particle size and the density of particles. Also, the rise velocity was found to be about 2.12m/s for the glass beads with a mean size of

0.358mm which is similar to that used in this study. The obtained value of Fan et al.[9] is higher than that of the present study since their column diameter is larger than that of the present study. Therefore, it may imply that the average rise velocity of smaller bubbles or voids in the turbulent flow regime increases with an increase in column diameter due to the less wall-effect.

CONCLUSIONS

The rise velocity of slugs in the slugging flow regime increases with an increase in gas velocity, while it remains almost constant with the variation of gas velocity in the turbulent flow regime. The rise velocity of smaller bubbles or voids can be utilized to determine the transition velocity from the slugging to the turbulent flow regime. The slug frequencies are found to be insensitive to an increase in gas velocity in the slugging flow regime within the frequency range of 0.47-0.64Hz.

A generalized correlation taking into account the particle properties and column size on the slug rise velocity in the slugging flow regime has been proposed based on the data of the present and previous studies.

ACKNOWLEDGEMENT

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NOMENCLATURE

D_t : bed diameter, m
$\bar{d}_p$: average particle diameter, m
f_s : slug frequency, Hz
g : gravitational acceleration, m/s^2
H_{mf} : bed height at minimum fluidization condition, m
H_{se} : bed height in a fixed bed, m
k : coefficient defined in Eq.(8)
L : distance between pressure taps, m
t : time, s
T : time period, s
x(t) : value of random variables sampled at time t
X(t) : random variables
Y(t) : random variables
$y(t+\tau)$: value of random variables sampled at time $t+\tau$
U_{is} : rise velocity of a isolated slug defined in Eq.(8), m/s
U_g : superficial gas velocity, m/s
U_{mf} : superficial gas velocity at minimum fluidization condition, m/s
U_{ms} : superficial gas velocity at the onset to the slugging flow regime, m/s
U_s : rise velocity of slugs, m/s
V_f : velocity of fluctuation waveform, m/s
V_{mt} : average rise velocity of smaller bubbles or voids at the onset to turbulent flow regime, m/s
V_t : rise velocity of smaller bubbles or voids in turbulent flow regime, m/s

Greek Letters

ρ_g : density of gas, kg/m^3
ρ_s : density of particles, kg/m^3
ϵ_{mf} : voidage of the bed at minimum fluidization condition
ϕ_s : spherity of particle
ϕ_{xy} : cross-correlation function between X(t) and Y(t) defined in Eq.(1)
μ : viscosity of gas, Pa. s
τ : shifted time, s
τ_m : transit time where the cross-correlation is maximum, s

Subscripts

c : calculated value
m : measured value

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