Korean J. Chem. Eng., **26**(2), 513-517 (2009)

Hydrodynamics of Geldart group A particles in gas-solid fluidized beds

Lii-Ping Leu† and Fu-Chien Tsai

Department of Chemical Engineering, National Taiwan University, Taipei 10617, Taiwan
(*Received 22 February 2008 • accepted 3 October 2008*)

Abstract−Geldart group A particles were fluidized in a 10 cm i.d.×1.8 m high Plexiglas-made bed with ambient air to determine the hydrodynamic properties in a gas-solid fluidized bed. The effects of static bed heights, position of pressure measuring points, differential and absolute pressure fluctuations on the hydrodynamic behavior of a Geldart group A particles in a gas-solid fluidized bed were investigated. The particles used in this study were 80 micrometer FCC powders and 60 micrometer glass beads. The variance of pressure fluctuations was used to find the minimum bubbling velocity. The obtained minimum bubbling velocity was compared with the other methods available in the literature. This method was found to be much easier and had better data reproducibility than the classical visual method or sedimentation method. The variance of pressure fluctuations increased due to the increase of superficial gas velocity and static bed height. The obtained minimum bubbling velocity and pressure fluctuations were found to depend on the measuring position along the axial direction. The effect of measuring position was discussed. Cross-correlation of two pressure signals was used to find the delay time, then the bubble rising velocity.

Key words: Group A Particles, Minimum Bubbling Velocity, Bubble Rising Velocity, Pressure Fluctuations

INTRODUCTION

The properties of gas-solid fluidized beds are strongly influenced by the bubble behavior including bubble formation, bubble growth, bubble coalescence and bubble movement. These bubble behaviors are difficulty to identify and measure, but they have strong relationship with the pressure fluctuations. The measurement of pressure fluctuations is a simple one even at the high temperature or high pressure condition. For Geldart group A particles [1], there is a bubbleless regime when the superficial gas velocity is greater than the minimum fluidization velocity but less than the minimum bubbling velocity. In the literature, the minimum bubbling velocity is usually determined by the visual or sedimentation method. Morooka et al. [2] studied the expansion of the fluidized beds. As soon as the bed reaches minimum fluidization velocity, it starts to expand. After bubbles start to form, the bed expands slowly and then its volume remains constant or even decreases with increasing superficial gas velocity; the volume of the emulsion phase is always smaller than at the bubble point. And they showed that at higher superficial gas velocity, the expansion ratio of emulsion is independent of gas velocity and bed diameter. They used $(L_e-L_m)/L_m$ vs. U_o and $(L_f-L_m)/L_m$ vs. U_o to find the minimum bubbling velocity. Choi et al. [3] used $(L_f-L_m)/L_m$ vs. U_o to determine the minimum bubbling velocity in the gas-solid fluidized beds at higher temperature. Abrahamsen and Geldart [4] used the following dimensional equation to find the minimum bubbling velocity:

$$U_{mb}=2.07\exp(0.716F)\,(d_p\,\rho_g^{0.06})/\mu^{0.347} \tag{1}$$

In industrial applications, especially for high temperature or high pressure situations, the values of L_e and L_f are not easy to determine or measure. But the pressure fluctuation signals are easy to measure even at high temperature or high pressure situations. The pressure fluctuations are often used for diagnosis of the fluidized beds or evaluating the operational parameters in gas-solid systems. Puncochar et al. [5] used the standard deviation of pressure fluctuations to find the minimum fluidization velocity of Geldart group B particles in gas-solid fluidized beds. Lee et al. [6] used the absolute and differential pressure fluctuations in the gas-solid fluidized beds to determine the transition velocity from bubbling to slugging fluidized regime. Leu and Pan [7] determined the minimum jet spouting velocity in the jet spout beds from the standard deviation of pressure fluctuations versus superficial gas velocity. The variance of pressure fluctuations was used here to find the minimum bubbling velocity. In this study the pressure fluctuation signals were measured for Geldart group A gas-solid fluidized beds at different measuring positions and different static bed heights. Cross-correlation of two pressure signals was used to find the delay time, then the bubble rising velocity.

EXPERIMENTAL

A 100 mm i.d.×1.8 m high Plexiglas-made fluidized bed was used for the experiments. The ambient air was used as the fluidization medium. FCC (fluid catalytic cracking) particles with average size of 80 μm and glass bead particles with average size 60 μm both belonging to Geldart group A were used as the bed materials. There were several pressure taps along the bed height at which the probe could easily be fixed and changed. The pressure probes were constructed from a 1.7 mm o.d. stainless steel tube covered with a 400 mesh screen to prevent solids in the bed from penetrating into the probes. The other side of the probe was connected to a pressure transducer. The obtained data were sent to a data acquisition system and PC, and stored for further treatment. The sampling frequency for pressure fluctuations was set at 100 Hz, and a total of 8192 data points were sampled.

†To whom correspondence should be addressed.
E-mail: lleulii@ntu.edu.tw

The mean value of the pressure fluctuations is calculated as

$$\bar{x}=\frac{1}{N}\sum_{i=0}^{N-1}x_i \tag{2}$$

and the variance of the pressure fluctuations is defined as

$$\sigma^2=\left[\frac{1}{N-1}\sum_{i=0}^{N-1}(x_i-\bar{x})^2\right]^{1/2} \tag{3}$$

The cross-correlation of two pressure signals x_i and y_i can be calculated as

$$R_{xy}(j)=\frac{1}{N-j}\sum_{i=0}^{N-1-j}x_i y_{i+j}, \quad 0\le j<N \tag{4}$$

The delay time $\tau=j\Delta t$ is determined from the cross-correlation function of two pressure signals. Then the bubble rising velocity is calculated as [8]

$$U_b=L_p/\tau \tag{5}$$

RESULTS AND DISCUSSION

For the gas flows through a particulate bed, at the beginning the bed is in the state of the fixed bed and the particles are motionless. As the superficial gas velocity increases beyond the minimum fluidization velocity, the fluidization begins. For Geldart group B particles, the bubbles form as soon as the superficial gas velocity exceeds the minimum fluidization velocity. The pressure fluctuations arise as the bubbles form and move through the beds. Puncochar et al. [5] found the standard deviation of pressure fluctuations of Geldart group B particles vs. superficial gas velocity is a straight line in a certain range. They used this property to determine the minimum fluidization velocity. For Geldart group A particles, when the superficial gas velocity is greater than the minimum fluidization velocity, no bubbles form until the minimum bubbling velocity. There is a bubbleless region between the minimum fluidization velocity and the minimum bubbling velocity. So the pressure fluctuations are zero until the superficial gas velocity is greater than the minimum bubbling velocity. Fig. 1 shows that the variance of pressure fluctuations versus the superficial gas velocity at various locations is a straight line. So the minimum bubbling velocity could be determined by the extrapolation. This method was in good agreement up to $U_o<4.62\ U_{mb}$ and $Re_p<15.4$.

Table 1. Physical properties of particles used in this study

Kind of particles	FCC particles	Glass bead particles
Particle size range (μm)	40-105	36-85
Average particle size (μm)	80	60
Density of particles (kg/m^3)	1850	2510
U_{mf} (m/s) (by experiment)	0.12	2.5

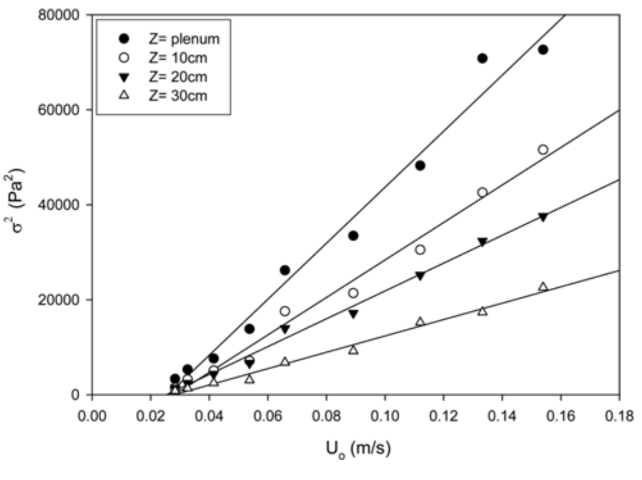

Fig. 1. The variance of absolute pressure fluctuations at various locations against superficial gas velocity for 60 μm glass bead particles (H_s=60 cm).

1. Absolute Pressure Measurement

Tables 2 and 3 show the minimum bubbling velocity for different measuring positions (probe locations) and different static bed heights for the absolute pressure measurement. For FCC particles the static bed height had nearly no influence on the minimum bubbling velocity, which is similar to the result reported by Morooka

Table 2. Comparison of U_{mb} for 80 μm FCC particles (absolute pressure measurement)

d_p (μm)	H_s (cm)	Probe location Z (cm)	U_{mb} by pressure fluctuations (cm/s)	U_{mb} by method of Morooka et al. (cm/s)	U_{mb} estimated based on Eq. (1) (cm/s)
80	30	plenum	0.125	0.178	0.511
		10	0.135		
		20	0.115		
	40	plenum	0.122		
		10	0.122		
		20	0.1185		
		30	0.12		
	60	plenum	0.134		
		10	0.13		
		20	0.1192		
		30	0.121		

Table 3. Comparison of U_{mb} for 60 μm glass bead particles (absolute pressure measurement)

d_p (μm)	H_s (cm)	Probe location Z (cm)	U_{mb} by pressure fluctuations (cm/s)	U_{mb} by method of Morooka et al. (cm/s)	U_{mb} estimated based on Eq. (1) (cm/s)
60	30	plenum	3.3	3.36	0.931
		10	2.4		
		20	2.6		
	40	plenum	3.2		
		10	2.66		
		20	2.66		
		30	2.66		
	60	plenum	2.73		
		10	2.8		
		20	2.8		
		30	2.8		

et al. [2], but the experimental values were lower than the value obtained by using Eq. (1). Morooka et al. considered that after fluidization to some extent, the gas velocity in dense phase does not change much. For glass bead particles at H_s=30 cm and 40 cm, respectively, the minimum bubbling velocity was almost independent of static bed height when the probe was put at the plenum. The values obtained were close to the one obtained by Morooka et al.'s method, but much higher than by using Eq. (1). But a lower value at H_s=60 cm was obtained. When the probe position was above the distributor, nearly the same value of minimum bubbling velocity was obtained regardless of different static bed heights.

For FCC and glass bead particles, the measuring position was almost no influence on the value of minimum bubbling velocity. For the probe at plenum, a higher value of minimum bubbling velocity was obtained.

A comparison of the obtained minimum bubbling velocity and other methods in the literature is also shown in Tables 2 and 3. The minimum bubbling velocity for FCC particles was lower than the value predicted by Abrahamsen and Geldart [4], but was close to the method by Morooka et al. [2]. The minimum bubbling velocity for glass beads was less than the value obtained by Morooka et al. method, but higher than by estimation based on Abrahamsen and Geldart.

2. Differential Pressure Measurement

Table 4. Comparison of U_{mb} for 80 μm FCC particles (differential pressure measurement-one probe at plenum)

d_p (μm)	H_s (cm)	Probe location Z (cm)	U_{mb} by pressure fluctuations (cm/s)	U_{mb} by method of Morooka et al. (cm/s)	U_{mb} based on Eq. (1) (cm/s)
80	30	plenum-10 cm	0.19	0.178	0.511
		plenum-20 cm	0.176		
	40	plenum-10 cm	0.1238		
		plenum-20 cm	0.1476		
		plenum-30 cm	0.15		
	60	plenum-10 cm	0.185		
		plenum-20 cm	0.159		
		plenum-30 cm	0.183		

Table 5. Comparison of U_{mb} for 60 μm glass bead particles (differential pressure measurement-one probe at plenum)

d_p (μm)	H_s (cm)	Probe location Z (cm)	U_{mb} by pressure fluctuations (cm/s)	U_{mb} by method of Morooka et al. (cm/s)	U_{mb} based on Eq. (1) (cm/s)
60	30	plenum-10 cm	3.57	3.36	0.931
		plenum-20 cm	3.42		
	40	plenum-10 cm	2.57		
		plenum-20 cm	2.85		
		plenum-30 cm	3.14		
	60	plenum-10 cm	1.71		
		plenum-20 cm	2.57		
		plenum-30 cm	3.71		

Table 6. Comparison of U_{mb} for 80 μm FCC particles (differential pressure measurement-both probes above the distributor)

d_p (μm)	H_s (cm)	Probe location Z (cm)	U_{mb} by pressure fluctuations (cm/s)	U_{mb} by method of Morooka et al. (cm/s)	U_{mb} based on Eq. (1) (cm/s)
80	40	10-20	0.173	0.178	0.511
		20-30	0.171		
	60	10-20	0.176		
		20-30	0.175		
		10-30	0.162		

Table 7. Comparison of U_{mb} for 60 μm glass bead particles (differential pressure measurement-both probes above the distributor)

d_p (μm)	H_s (cm)	Probe location Z (cm)	U_{mb} by pressure fluctuations (cm/s)	U_{mb} by method of Morooka et al. (cm/s)	U_{mb} based on Eq.(1) (cm/s)
60	40	10-20	3.46	3.36	0.931
		20-30	3.33		
	60	10-20	3.45		
		20-30	3.43		
		10-30	2.63		

2-1. One Probe-Plenum. The Other Probe-Above Distributor

Tables 4 and 5 show the minimum bubbling velocity obtained for different measuring positions (probe locations) and different static bed heights for the differential pressure measurements with one probe fixed at the plenum and the other one at position above the distributor. When the distance between the probes became larger, the minimum bubbling velocity value increased. The reason was probably due to the large distance between the probes which resulted in the large pressure fluctuations. Using this technique, the minimum bubbling velocity value obtained was less than the value for the absolute pressure measurement.

2-2. Both Probes Above the Distributor

Tables 6 and 7 show the minimum bubbling velocity obtained for different measuring positions (probe locations) and different static bed heights for the differential pressure measurement with both two probes at position above the distributor. The static bed height nearly had no influence on the minimum bubbling velocity.

For the differential pressure measurement, the obtained minimum bubbling velocity was close to the value from the Morooka et al. method but smaller than the value compared to the prediction by Abrahamsen and Geldart [4] for the FCC particles. For the glass bead particles, the obtained minimum bubbling velocity was close to the value from Morooka et al. method but higher than the value predicted by Abrahamsen and Geldart [4].

3. Bubble Rising Velocity

In this study, two pairs of 8192 pressure fluctuation data obtained at the two different pressure probes above the distributor were taken for the calculation of one delay time. Fig. 2 shows the frequency distribution of 40 and 15 delay time data by the same procedure.

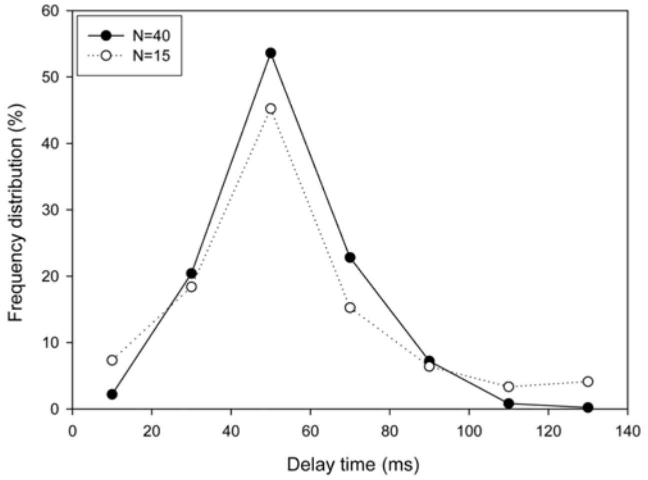

Fig. 2. The distribution of delay time of 80 μm FCC particles at U_o=0.658 cm/s (probe at 5 cm and 10 cm above distributor).

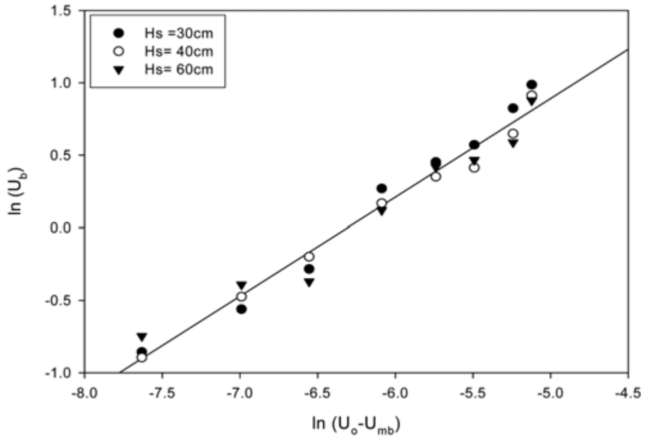

Fig. 3. Bubble rising velocity for 80 μm FCC particles (probe at 10 cm and 20 cm above distributor).

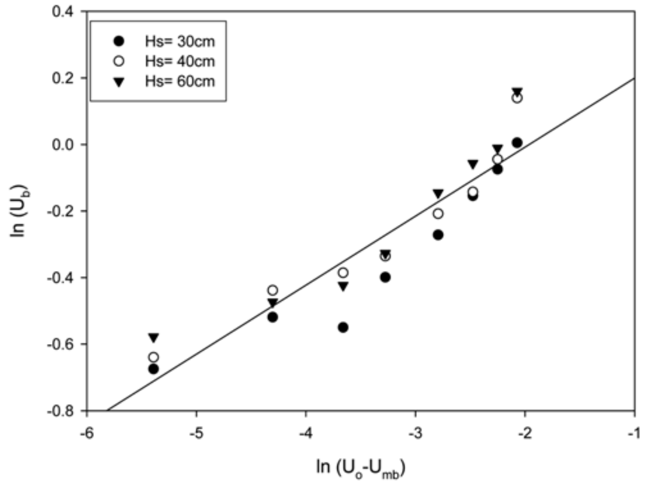

Fig. 4. Bubble rising velocity for 60 μm glass bead particles (probe at 10 cm and 20 cm above distributor).

From this figure it was found that the distribution of delay time approached a certain value. In this way the average delay time was

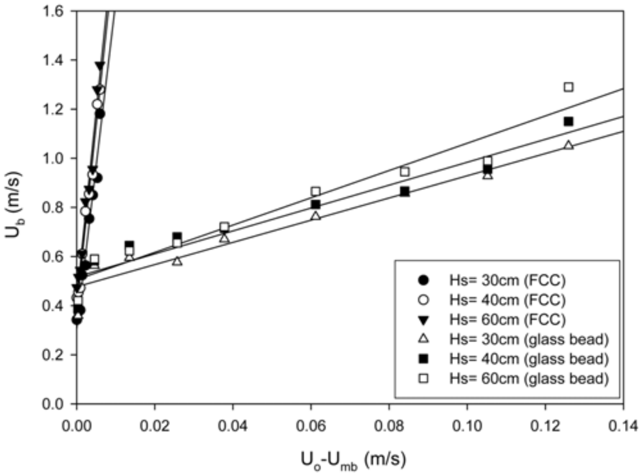

Fig. 5. The bubble rising velocity vs. U_o-U_{mb} (differential probe at 5 cm and 10 cm above distributor).

determined. The bubble rising velocity for FCC particles and glass beads is shown in Figs. 3 and 4, respectively. The static bed height did not have much effect on the bubble rising velocity for the FCC particles, but for the glass bead particles, the bubble rising velocity increased with increase of static bed height, although the effect was not very obvious.

The bubble rising velocity vs. (U_o-U_{mb}) is shown in Fig. 5 for FCC particles and glass bead particles at different static bed heights. A minimum bubble rising velocity was found from the figure for FCC particles (=0.42 cm/s) and glass beads (= 0.51cm/s). This result was in agreement with the result of the two phase theory of Toomey and Johnstone [9] who described the bubble rising velocity as

$$U_b=(U_o-U_{mf})+0.711\,(g\,d_b)^{1/2} \tag{6}$$

For Geldart group A particles, at $U_o \le U_{mb}$, d_b=0; thus a minimum bubble rising velocity was obtained.

It was shown in the figure that the bubble rising velocity for FCC particles was not influenced by the static bed height. For glass bead particles the static bed height had an effect on the bubble rising velocity; it could be also found from Fig. 4.

The obtained bubble rising velocity could be correlated as

$$U_b=(U_o-U_{mf})+9.21\,(U_o-U_{mf})^{0.41} \tag{7}$$

with correlation coefficient 0. 904 for FCC particles, and

$$U_b=(U_o-U_{mf})+1.54\,(U_o-U_{mf})^{0.24} \tag{8}$$

with correlation coefficient 0.917 for glass bead particles.

From Figs. 4 and 5, it appears that the static bed height H_s had an effect on U_b, but at present time it is hard to find a correlation equation taking into consideration the effect of H_s. Further investigation should be done before the conclusion is made.

4. Comparison of Pressure Fluctuations for Geldart Group A and B Particles

The comparison of dimensionless standard deviation of pressure fluctuations of Geldart group A and B particles [10] versus dimensionless velocity is shown in Fig. 6; for Geldart group B particles, $U_{mb}=U_{mf}$. The standard deviation of pressure fluctuations/average pressure drop of Geldart group B particles was higher than the value

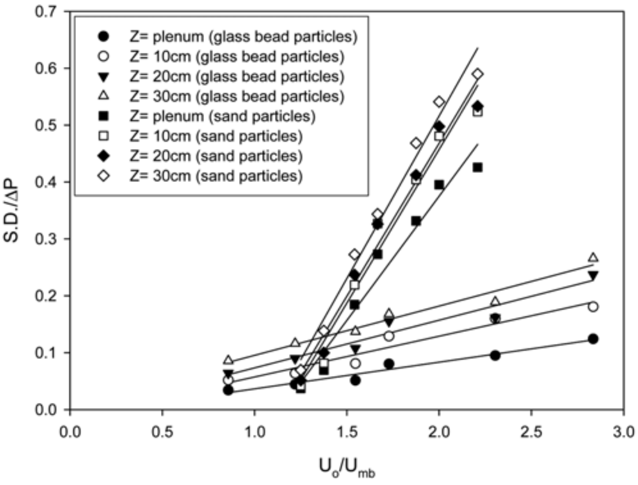

Fig. 6. The dimensionless standard deviation of pressure fluctuations at various locations against dimensionless gas velocity for 60 μm glass bead particles and 163 μm sand particles (H_s=60 cm) [10].

of Geldart group A particles. Usually, the fluidization quality is based on the standard deviation of pressure fluctuations. The Geldart group A particles had a lower value of pressure fluctuations than the Geldart group B particles. The small pressure fluctuations meant small bubble movement in the bed and more uniform bed structure. Thus the Geldart A particles had a better fluidization quality.

CONCLUSION

A 100 mm i.d.×1.8 m high Plexiglas-made fluidized bed was used for the experiments. Ambient air was used as the fluidization medium. Geldart group A FCC particles and glass bead particles were used as the solid particles in the beds. The following conclusions were obtained:

1. For U_o<4.62 U_{mb} and Re_p<15.4, the variance of pressure fluctuations vs. superficial gas velocity was a straight line, and the minimum bubbling velocity was found by extrapolation. This method was simple and easy to use to find the minimum bubbling velocity.

2. The obtained minimum bubbling velocity and pressure fluctuations were found to depend on the measuring position along the axial direction.

3. Bubble rising velocity was increased with the static bed height for glass bead particles. For FCC particles the static bed height did not have an effect for bubble rising velocity. A minimum bubble rising velocity existed for Geldart group A particles.

4. For same U_o/U_{mb} value, the pressure fluctuations/average pressure drop for Geldart group A is less than for group B particles.

NOMENCLATURE

d_p : mean particle size [m]
F : fine fraction less than 45 μm [-]
H_s : static bed height [m]
i : integer [-]
j : integer [-]
L_c : completely settled bed height [m]
L_e : height of emulsion phase [m]
L_f : bed height [m]
L_m : static bed height [m]
L_p : distance between two probes [m]
N : integer number [-]
P : pressure [Pa]
$R_{xy}(j)$: cross-correlation of signals x and y [Pa^2]
Re_p : particle reynolds number [-]
S.D. : standard deviation of pressure fluctuations [Pa]
Δt : time interval [s]
U_b : bubble rising velocity [m/s]
U_{mb} : minimum bubbling velocity [m/s]
U_{mf} : minimum fluidization velocity [m/s]
U_o : superficial gas velocity [m/s]
$\bar{x}$: mean of pressure fluctuations [Pa]
x_i : pressure fluctuation signal [Pa]
y_i : pressure fluctuation signal [Pa]
Z : probe location [m]
μ : viscosity of gas [Pa s]
ρ_g : density of gas [kg/m^3]
σ^2 : variance of pressure fluctuations [Pa^2]
τ : time lag in cross-correlation of two signals [s]

REFERENCES

1. D. Geldart, *Powder Technol.*, **7**, 285 (1973).
2. S. Morooka, M. Nishinaka and Y. Kato, *Kagaku Kogaku Ronbonshu*, **37**, 485 (1973).
3. J. H. Choi, T. W. Kim, Y. S. Moon, S. D. Kim and J. E. Son, *Powder Technol.*, **131**, 15 (2003).
4. A. R. Abrahamsen and D. Geldart, *Powder Technol.*, **26**, 35 (1980).
5. M. Puncochar, J. Drahos, J. Cermak and K. Selucky, *Chem. Eng. Commun.*, **35**, 81 (1985).
6. S. H. Lee, S. D. Kim and S. H. Park, *Korean J. Chem. Eng.*, **19**, 1020 (2002).
7. L. P. Leu and R. S. Pan, *Can. J. Chem. Eng.*, **82**, 1044 (2004).
8. O. Sitnai, *Chem. Eng. Sci.*, **37**, 1059 (1982).
9. R. D. Toomey and H. F. Johnstone, *Chem. Eng. Prog.*, **48**, 220 (1952).
10. T. B. Liu, *Pressure fluctuations in bubbling fluidized beds*, MS thesis, Department of Chemical Engineering, National Taiwan University, Taipei, Taiwan (2004).