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Characteristics of Slug Flow in a Fluidized Bed of Polyethylene Particles

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Abstract−The slug flow behavior of polyethylene particles was examined in a fluidized bed of 7 cm ID and 50 cm in height. The employed polymer particles were high density polyethylene (HDPE) with the average particle size of 603 μm. The slugging flow of polyethylene particles was analyzed from the measured pressure drop signals by classical statistical methods such as absolute average deviation, probability density function, power spectrum, auto-correlation, and cross-correlation. The results show that in spite of high dielectric constant of polymer particles, the slugging phenomena such as incipient slugging velocity, slugging frequency and slugging rise velocity were very similar to the Geldart B type non-polymeric particles. It was observed that slug frequencies decreased with gas velocity and the limiting slug frequency was observed for the gas velocities in this study.

Key words: Fluidized Bed, Slugging, Polyethylene

INTRODUCTION

Fluidized beds are increasingly being used for catalytic polymerization, in particular the polymerization based on Ziegler-Natta catalyst (e.g. UNIPOL process) because of a significant reduction in the operating and fixed costs [Choi and Ray, 1985; Ko et al., 1999]. Unfortunately, there is only little published information concerning the hydrodynamic behavior of this important fluidized bed type of olefin polymerization reactor [Cho et al., 2001; Lee et al., 2001]. In particular, there is not a quantitative understanding of the bubbling and slugging flow regimes of a fluidized bed of polymer powders. Since physical properties of particles affect the flow pattern in a fluidized bed, the nature of pressure fluctuation in a slugging fluidized bed of polymer particles is required to understand the commercial fluidized bed polymerization reactor for polyethylene production.

In order to elucidate the slugging flow behavior of polymer particles in the fluidized bed, we studied the probabilistic and statistical characteristics of pressure fluctuation along the fluidized bed of high density polyethylene (HDPE).

In this study, the effect of the gas velocity, contents of fine powder, and particle size on the slug flow frequency and slug rise velocity at the various axial bed positions were investigated.

EXPERIMENTAL

The experimental test set-up is shown in Fig. 1. The fluidized bed column was made of acrylic pipe of 7 cm ID and 50 cm in height and was connected to a cyclone. The disengaging section was located between the fluidized bed column and the cyclone as shown in Fig. 1. It was designed to simulate the dimensional similarity of a commercial fluidized bed reactor of the UNIPOL process. Air was supplied from the compressor by way of a calibrated flow meter and introduced to the bottom of the bed through the perforated distributor. The static bed height was 75% of the bed volume and it was about 37 cm above the distributor. Three differential pressure transducers (Cole-Palmer. T40) were mounted at the lower and upper

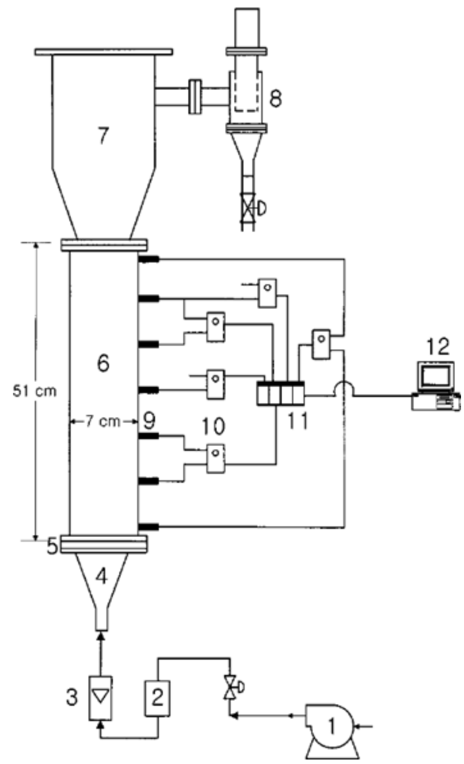

Fig. 1. Experimental test facility.

1. Blower	7. Disengaging section
2. Filter & Regulator	8. Cyclone separator
3. Rotameter	9. Pressure tap
4. Calming section	10. Pressure transducer
5. Distribution plate	11. A/D converter
6. Fluidization column	12. PC

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section of the bed in order to measure local pressure drop in the bed and the other one was employed to measure the pressure drop of the overall bed. The lower section of the bed was defined where the pressure taps located between the 14 cm and 19 cm above the distributor and the upper section of the bed was defined where the pressure taps were located between 28 cm and 33 cm above the distributor. The overall pressure drop of the bed was measured through the pressure taps located between 5 cm and 40 cm above the distributor. The measured pressure drops at the lower, upper and overall bed were transferred to the data acquisition unit and stored in the personal computer. The sampling rate of pressure drop was 100 Hz and sampling time was 80 seconds after the fluidized bed reached the steady-state condition. Therefore 8,000 pressure signals were collected for each run. The operating gas velocity covered the 1.2-5.0 U_{mf} ranges and the slug flow was observed for that gas velocity range.

High density polyethylene (HDPE) particles, provided by the Hanwha Petrochemical plant in Korea, were used as the bed materials. The supplied HDPE powders showed wide size distributions (100-1,000 μm) and several different particle sizes were prepared from the sieving.

The physical properties of HDPE powders and operating conditions of this experiment are given in Tables 1 and 2, respectively.

1. Statistical Analysis of Pressure Drop Signals

In order to analyze the time series of pressure drop fluctuation in a slugging fluidized bed, several classical statistical methods for signal were employed.

1-1. Average Absolute Deviation (AAD)

As a measure of the amplitude of the signal, the average absolute deviation of the signal from its average was used. As the probability distributions of the pressure fluctuation are not at all similar to the normal distribution, the linear measure of absolute deviation is considered to be a better measure than the standard deviation [Stappen et al., 1993].

$$AAD = \frac{1}{N}\sum_{r=1}^{N}|x_r - \bar{x}| \quad (1)$$

1-2. Autocorrelation Coefficient

A useful measure of the predictability of a signal is the auto-correlation coefficient, which is defined as:

$$a_c(\tau) = \frac{\int_{r=1}^{N-\tau}[x(t)-\bar{x}][x(t+\tau)-\bar{x}]dt}{\int_{r=1}^{N}[x(t)-\bar{x}]^2 dt} \quad (2)$$

Where x(t) is the measured signal, τ is the time lag, and the $\bar{x}$ is the mean value of the signal x(t). The correlation coefficient of a periodic signal produces a periodic function $a_c(\tau)$. It is possible to estimate the slug frequency from the auto-correlation coefficient by estimating the time between τ=0 and the first peak of the auto-correlation coefficient [Karamavruc and Clark, 1997].

1-3. Power Spectrum

Any signal can be represented as a superposition of the periodic components. Generally, the determination of relative strengths is called spectral analysis. The power spectrum indicates how the energy is distributed over the frequencies. If the power spectrum exhibits broad band noise at low frequencies, it is an indication of a highly irregular signal [Karamavruc and Clark, 1997].

$$P(\omega) = |F(\omega)|^2 = \left|\frac{1}{2\pi}\int_{-\infty}^{\infty} x(t)\exp(-i\omega t)dt\right|^2 \quad (3)$$

1-4. Probability Density Function

For a continuous stationary random variable x(t), its probability density function $f_{x(t)}(x)$ can be calculated as:

$$f_{x(t)}(x)\Delta x = \lim_{T\to\infty}\frac{1}{T}\sum(\Delta T) \quad (4)$$

where T represents the total sampling time.

The probability density function itself showed the characteristic properties of the pressure fluctuations and the distribution of measured signals [Fan et al., 1981].

Table 1. Physical properties of employed High Density Polyethylene (HDPE)

Parameter	Value
Particle diameter, d_p	603 μm
Particle density, ρ_s	0.82 g/cm^3
Particle bulk density, ρ_b	0.44 g/cm^3
Voidage at incipient fluidization, ε_{mf}	0.46
Minimum fluidization velocity, U_{mf}	10.5 cm/s

Table 2. Experimental conditions

Bed diameter, D_t	7.0 cm
Bed height, H	50 cm
Static bed height, H_{se}	37 cm
Distributor type	Perforated plate with screen
Pressure tap location	14, 28 cm above the distributor
Pressure tap interval	5 cm
Sampling rate	100 Hz
Sampling data numbers	8000
Gas velocity Range, U/U_{mf}	1.2-4.8
Fines content	0, 1, 5%

RESULTS AND DISCUSSION

1. Incipient of Slug Flow

The typical pressure drops signals obtained at the lower and the upper section of the bed with different gas velocity are shown in Figs. 2 and 3, respectively. As these figures show, the pressure fluctuations increase with gas velocity and the periodic motion of slug can be observed from the gas velocity of U_g=2 U_{mf} at the upper section of the bed and gas velocity of U_g=2.8 U_{mf} at the lower section of the bed. The onset of slugging is caused by the coalescence of upward flowing bubbles that occupy the whole cross section of the bed. Thus when slugging occurs, there is a large pressure drop fluctuation. From the pressure signals shown in Figs. 2 and 3, it can be said that the incipient slugging velocity could be between a gas velocity of U_g=1.2 U_{mf} and 2.0 U_{mf}. It is also clear that the formation of larger bubbles through bubble coalescence in the middle section of the bed, the formation of small bubbles near the distributor, all affect the pressure fluctuations in the bed and the major pressure fluctuations are caused by the formation of slugs due to bubble co-

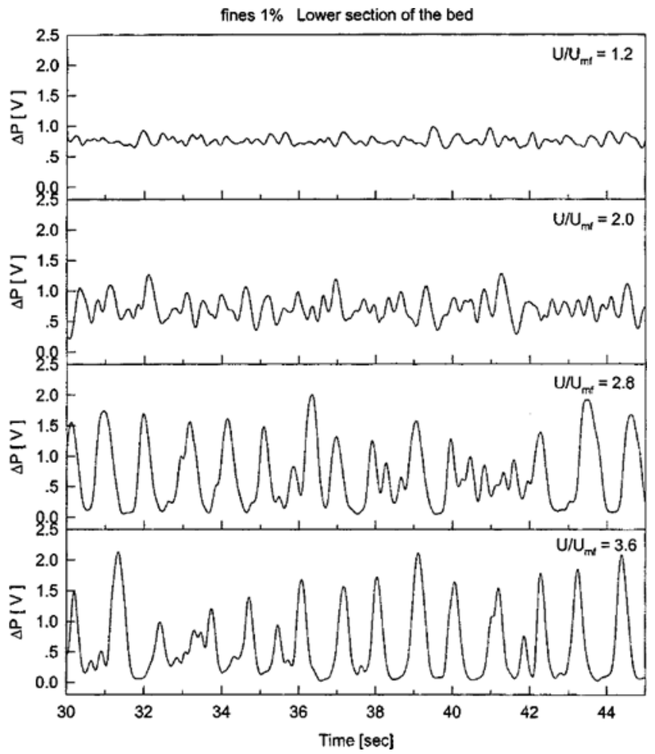

Fig. 2. Pressure fluctuation signals at the lower section of the bed.

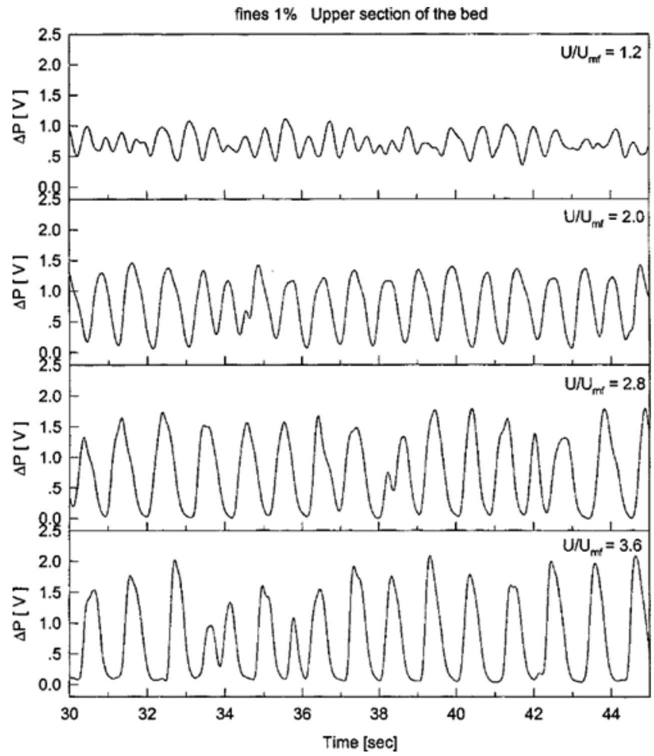

Fig. 3. Pressure fluctuation signals at the upper section of the bed.

alescence. The onset of slugging can also be determined from the power spectrum of the frequency of slug, since another characteristic of slugging can be recognized by the definite constant frequency of pressure drop fluctuation [Satija and Fan, 1985]. As the flow approached to slugging, the higher frequencies disappeared and it is expected that there is a dominant frequency for slugging. Figs. 4 and 5 show the power spectrum of signals at the lower and the upper section of the bed with different gas velocity. For the upper section of the bed, we can see the dominant frequency of 1.3 Hz at a gas velocity of U_g=1.6 U_{mf} and the dominant frequency of the system converged to 1.0 Hz with the increase of gas velocity. Since the minimum gas velocity for fluidization for 500 micron polyethylene par-

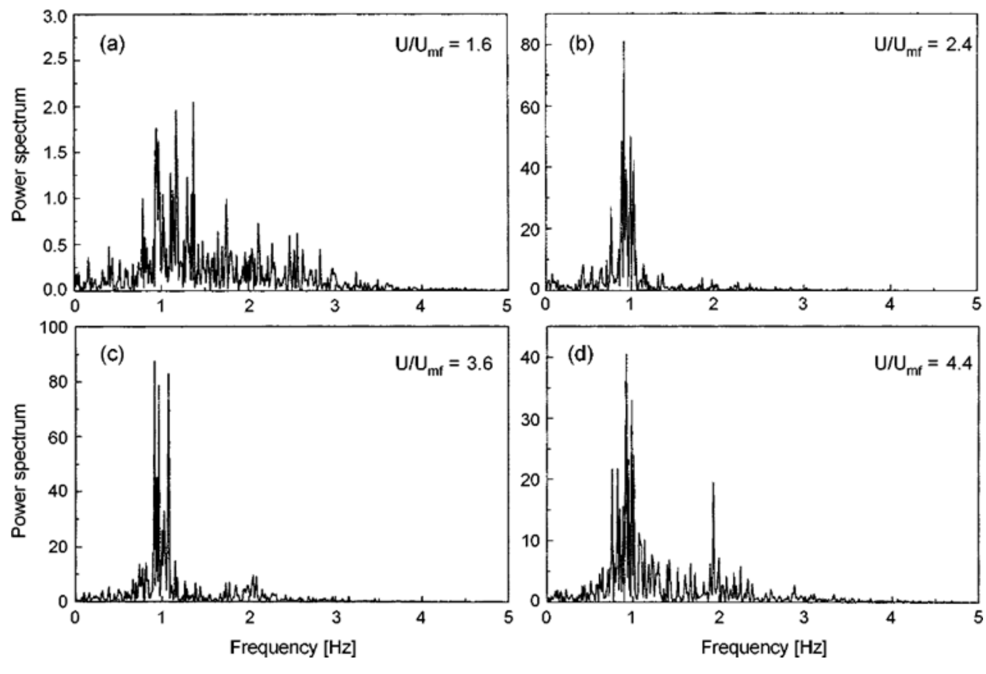

Fig. 4. Power spectrum of signal at the lower section of the bed.

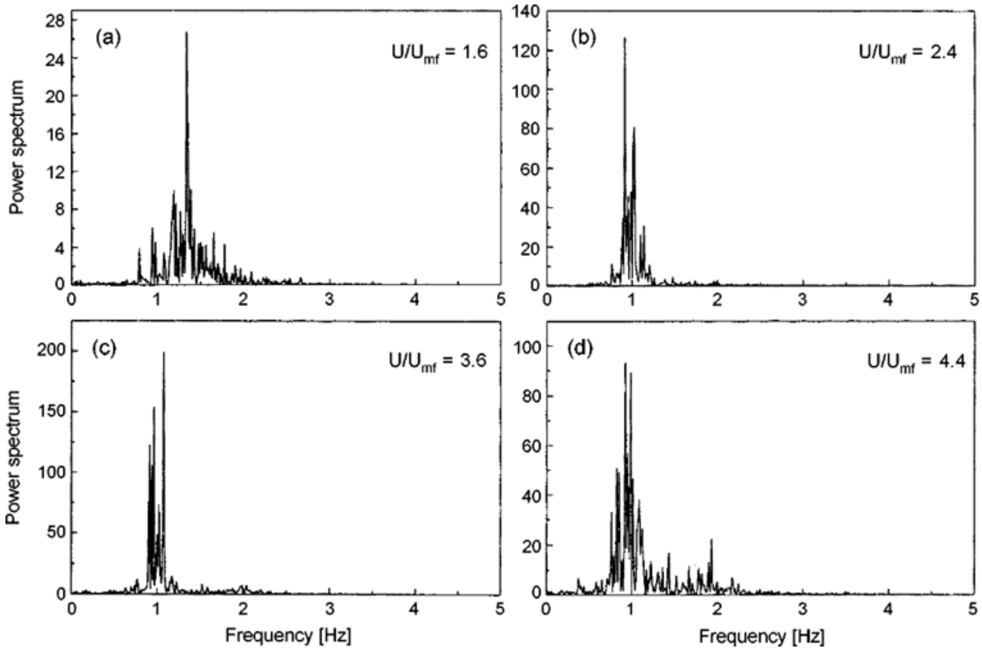

Fig. 5. Power spectrum of signal at the upper section of the bed.

ticles was 10.7 cm/s, it was suggested that minimum slugging gas velocity (U_{ms}) for this system is 17 cm/s. However, as discussed before, for the lower section of the bed, the dominant frequency of the system begins at a gas velocity of U_g=2.4 U_{mf}. Therefore, it can be said that these power spectra of pressure drop signals give the more qualitative evidence of minimum slugging velocity than suggested value from the pressure drop signals. Researchers have developed several correlations that predict the minimum slugging velocity [Stewart and Davidson, 1967; Baeyens and Geldart, 1974; Broadhurst and Becker, 1975; Ho et al., 1983]. Because of similar operating conditions of this study, the proposed correlation of Baeyen and Geldart [1974] for minimum superficial gas velocity for slugging was used for the comparison as given in Eq. (5).

$$U_{ms}=U_{mf}+1.6\cdot 10^{-3}\,(60\,D\,0.175-H_{mf})^2+0.07\,(g\,D)^2 \qquad (5)$$

The predicted value of U_{ms} by using Eq. (5) was 19.0 cm/s. Therefore the proposed correlation for the prediction of gas velocity for incipient slug flow was good enough for the polymer particles employed in this experiment and it seems that there was not a strong effect of polymer particle of high value of dielectric constant

2. Slug Frequency and Slug Rise Velocity

The power spectrum data can be used as the measure for prediction of slug frequency. During the slug flow, the dominant slugging frequency can be qualitatively obtained from the power spectrum data. The power spectrum data were calculated from measured pressure signals through the Eq. (3) as discussed in the previous section. Fig. 5 shows the power spectrum data obtained at the upper section of the bed with different gas velocities. From the Fig. 5(b), which is the power spectrum data at the gas velocity of U_g= 2.4 U_{mf} with 603 μm HDPE particles, for example, we can clearly see the sharp peak at a frequency of 1.0 Hz. Therefore, at this operating condition it can be said that the dominant frequency of slug flow is 1.0 Hz. The dominant frequency determined from the power

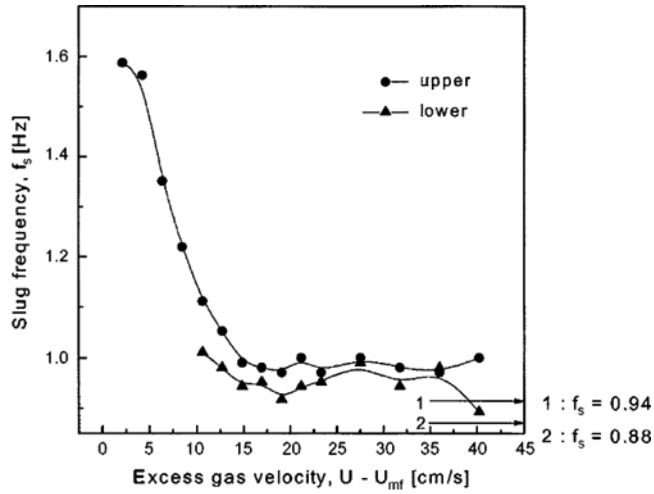

Fig. 6. The variation of slug frequency with gas velocity.

spectrum data was defined as the slug frequency in this study.

The variation of the slug frequency determined in this study for polyethylene particles with the gas velocity at different bed height is shown in Fig. 6. The slug frequency was found to decrease with an increase in gas velocity and it appeared to approach a limiting value.

The slug rise velocity was also investigated in a slugging fluidized bed of polyethylene particles. In this study the slug rise velocity was determined by calculating the cross-correlation function of the two signals obtained from the pressure transducers at the lower and upper section of the bed. Fig. 7 shows a typical cross-correlation function obtained for 603 μm HDPE particles at a gas velocity of 21 cm/s. In order to examine the particle size effect on the slug rise velocity, we used 603 μm, 392 μm and 1,075 μm HDPE par-

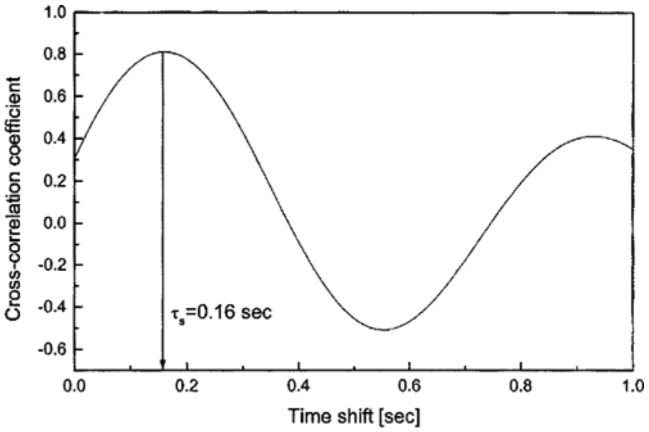

Fig. 7. An example of cross-correlation at the gas velocity of U_g= 21 cm/sec.

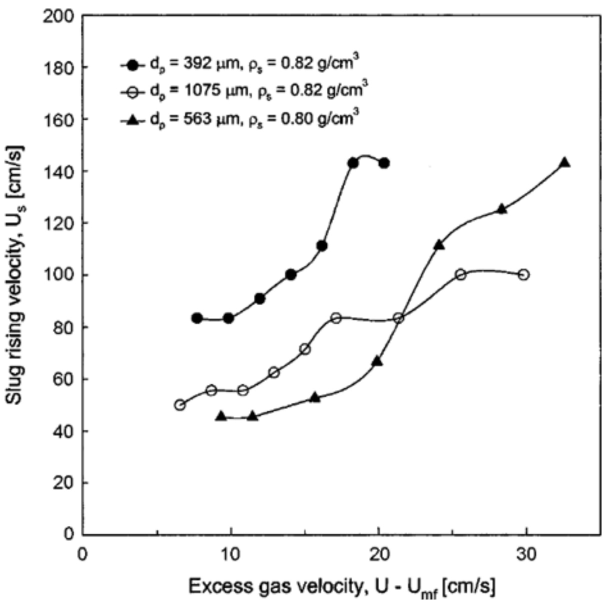

Fig. 8. Particle size effect on the slug rise velocity.

ticles. The variation of the slug rise velocity calculated from the cross-correlation function with gas velocity for 392 μm and 1,075 μm polyethylene particles is shown in Fig. 8. It can be seen that the slug rise velocity increased with gas velocity and reached a maximum value for the tested gas velocity ranges. This finding is consistent with the experimental results of Baker and Geldart [1978], Geldart et al. [1978], and Fan et al. [1983]. Fig. 8 also shows the particle size effect on the slug rise velocity. It is clear that slug rise velocity decreases with an increase of particle size. It can be explained that larger particles provide less resistance to the fluidizing medium as compared to smaller particles [Broadhurst and Becker, 1975; Baeyen and Geldart, 1973]; thus for the larger particles the excess gas velocity, ($U-U_{mf}$), required for a bed to achieve slugging, was small when compared to particles of lesser diameter [Broadhurst and Becker, 1973].

3. Effect of Content of Fine Powders

In general, polymerization in a fluidized bed inevitably produces fine powders, and it is believed that a significant amount of this fine

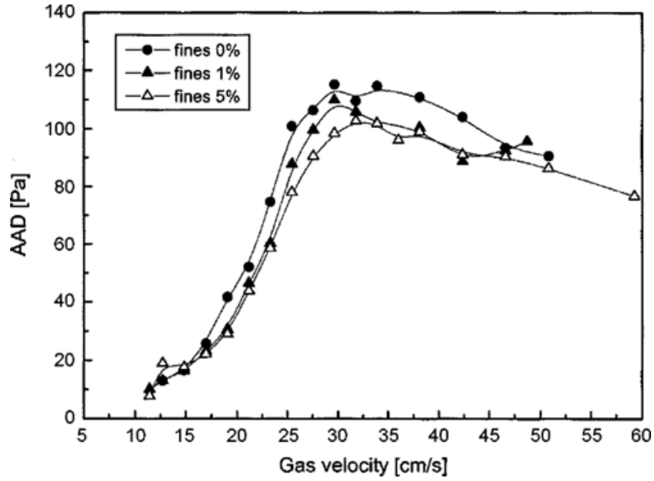

Fig. 9. AAD of pressure fluctuation at the lower section of the bed.

powder sometimes causes a shutdown of the fluidized bed reactor. Therefore, it may be valuable to examine the effect of fine contents on the slugging flows in a fluidized bed. The fine powders in this study were defined as HDPE powder that is smaller than 120 microns.

The average absolute deviation (AAD) of pressure drop fluctuation measured at the lower section of the bed with different fine powders contents is shown in Fig. 9. As can be seen, the ADD values increased with gas velocity for three different fine powder content and the ADD values decreased with fine powder content. This trend was also observed at the upper section of the bed and at the whole section of the bed. This implies that this increased amount of fine powder somehow reduced the pressure drop fluctuation in a slugging fluidized bed. Another interesting comparison about the content of fines on slugging frequency is found from the power spectrum. Fig. 10 shows the difference of dominating frequency for different fine powders contents. From the Fig. 10, we can easily see that at the higher fine powder content, the dominating frequency was larger than that of lower fine powder content and this may mean that slugging was occurring a little bit more frequently and the distribution of the slug was wider. The experimentally obtained pressure drop signal in a slugging fluidized bed with different fine pow-

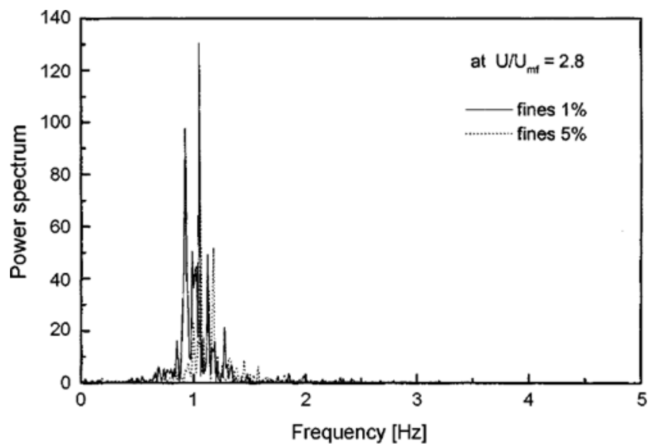

Fig. 10. Effect of content of fine powders on the slug frequency.

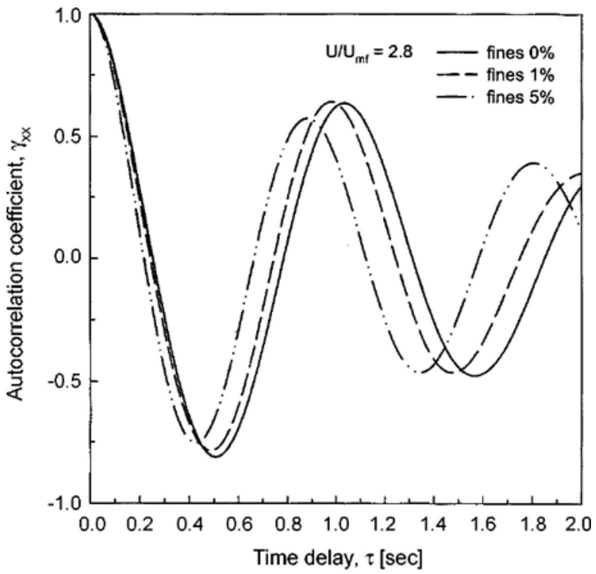

Fig. 11. Auto-correlation coefficient at the upper section of the bed.

ders contents was analyzed by the auto-correlation coefficient. Fig. 11 shows the auto-correlation coefficient of pressure drop signal at the upper section of the bed. From Fig. 11, it can be seen that at the higher fine powder content the time lag was shorter than that at the lower fine powder content. Therefore, it can be concluded that at the higher fine powder content, slugging occurred more frequently, and from the magnitude of the auto-correlation coefficient the occurrence of slugging was less periodic than that of lower fine powder contents. Even though it is not clear that the more frequent slugging flow in the bed at the higher fine powders content caused the shutdown of the fluidized bed reactor, different flow characteristics were observed with different fine powder contents.

CONCLUSIONS

The slug flow characteristics of polyethylene particles in a fluidized bed were investigated. Statistical analysis methods such as probability density function, auto-correlation cross-correlation, and power spectrum were employed to analyze the measured pressure fluctuation data at various axial locations. The experimental results showed that the magnitude of pressure drop fluctuation increased with gas velocity. The pressure fluctuations were smaller and more irregular at the lower section of the bed than that of the upper section of the bed. Pressure drop fluctuation was smaller and showed wide distribution of power spectrum below the slug flow regime. At the slug regime pressure the drop fluctuation was larger and a narrow distribution of power spectrum data was obtained. The dominant frequency of the slug converged to 1.0 Hz as the gas velocity increased. As the content of fine powders increased, the magnitude of pressure fluctuations was decreased and this trend was also observed from analysis of probability density function and average absolute deviation. The slug frequency calculated from the auto-correlation function and power spectrum showed that slug frequency was increased with gas velocity and content of fine powder. The limiting slug frequency that was independent of particle properties and gas velocity was obtained, and it was increased with the content of fine powder. This means that slugging occurred more frequently with higher content of fine powder in the fluidized bed.

NOMENCLATURE

A : cross-section area of fluidized bed [cm^2]
d_p : particle diameter [cm]
D_t : bed diameter [cm]
f_s : slug frequency [Hz]
g : gravitational acceleration [cm/s^2]
g_c : gravitational conversion factor [$g\text{-}cm/g_f\text{-}s^2$]
H : bed height [cm]
H_{mf} : bed height at incipient fluidization [cm]
N : total sampling number [-]
ΔP : pressure drop [Pa, g_f/cm^2]
U_g : superficial gas velocity [cm/s]
U_{mf} : minimum fluidizing velocity [cm/s]
U_{ms} : minimum slugging velocity [cm/s]
t : time [sec]
T : total sampling time [sec]

Greek Letters
α : weight fraction of fines in the bed [-]
τ : time delay [sec]
ω_o : fundamental frequency [rad/s]

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