Korean J. Chem. Eng., **16**(5), 677-683 (1999)

An Analysis of Pressure Drop Fluctuation in a Circulating Fluidized Bed

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(*Received 14 April 1999 • accepted 8 June 1999*)

Abstract–The characteristics of pressure drop fluctuation in a 5.0 cm I.D.×250 cm high circulating fluidized bed with fine polymer particles of PE and PVC were investigated. The measurements of time series of the pressure drop were carried out along the three different axial locations. To determine the effects of coarse particles and relative humidity of air on the flow behavior of polymer powders-air suspension in the riser, we employed deterministic chaos analysis of the Hurst exponent, correlation dimension and phase space trajectories as well as classical methods such as standard deviation, probability density function of pressure drop fluctuation. From a statistical and chaos analysis of pressure fluctuations, the upper dilute region was found to be much more homogenous flow compared to that in the bottom dense region at the same operating conditions. It was also found that the addition of coarse particles and higher humidity of air reduced the pressure fluctuations, thus enhancing flow stability in the riser. The analysis of pressure fluctuations by statistical and chaos theory gave qualitative and the quantitative information of flow behavior in the circulating fluidized bed.

Key words : Circulating Fluidized Bed, Pressure Drop Fluctuation, Hurst Exponent, Correlation Dimension

INTRODUCTION

It has been estimated that circulating fluidized beds are one of the most promising devices for gas-solids operations as technology for physical operation and chemical reactions with frequent contacts between high velocity gases and solid particles of small size.

Circulating fluidized beds are very different from conventional bubbling fluidized beds in terms of hydrodynamic behavior and heat transfer characteristics. Circulating fluidized beds have advantages of higher contacting efficiency and high processing capacity over bubbling fluidized beds [Yerusalmi, 1979]. In order to make use of these advantages, we have to understand entirely the hydrodynamic behavior of a circulating fluidized bed. One of the essential properties to indicate flow characteristics in a fluidized bed is the measurement of pressure drop fluctuations. The time series of pressure drop fluctuation indicates the instantaneous solid particle distribution per unit volume of the bed and the flow of gas-solid suspension. Therefore, this is very useful information for understanding flow characteristics in a fluidized bed.

The gas-solid two-phase flow in a circulating fluidized bed prevents us from forecasting solid distribution and velocity gradient of the axial and radial direction from process modeling because of particle-particle, particle-wall, particle-gas interaction, particle agglomeration, and turbulence.

The measurement of pressure drop signals has been analyzed by using standard deviation, probability density function, and power spectral density function. But in recent studies, the circulating fluidized bed hydrodynamics was regarded to be a chaotic system and analyzed by chaotic time series analysis using deterministic chaos theory because of the limitations and uncertainty of these conventional methods.

Schouten and van den Bleek [1992, 1993] indicated that the hydrodynamics of gas-solid fluidization shows chaotic behavior and suggested that the deterministic chaos theory offers new and useful quantitative tools to characterize the non-linear dynamic behavior of fluidized beds. Daw and Hallows [1993] measured the pressure drop and voidage in a gas fluidized bed and demonstrated chaotic hydrodynamics of fluidized beds based on the deterministic chaos theory. Kang et al. [1997] and Fan et al. [1990] analyzed the complicated and stochastic characteristics of circulating fluidized beds and three-phase fluidized beds based on the concept of fractals, respectively. In particular, pressure fluctuation in a gas-solid fluidized bed have been analyzed in terms of Hurst rescaled range analysis, thus yielding the estimates for the so-called Hurst exponent. Kikuchi et al. [1996] measured time series data of bubble and particle frequencies in gas-liquid-solid fluidized beds by a novel optical transmittance probe with a narrowed laser beam and analyzed them using correlation dimension. Franca et al. [1991] calculated the power spectral density function and probability density function and also fractal techniques to classify the various flow regimes in a bubbling fluidized bed. Bouillard and Miller [1994] examined the experimental time series of differential pressure fluctuations along the riser height of a circulating fluidized bed reactor and reported that the hydrodynamic behavior of the circulating fluidized bed appeared to be chaotic using power spectral density and correlation dimension. Karamavruc et al. [1995] demonstrated that a mutual information function was used to identify the periodicity and predictability of local instantaneous differential pressure and temperature signals. The first minimum of the mutual information function provides the optimum time delay to reconstruct the phase space portrait from one-dimensional time series.

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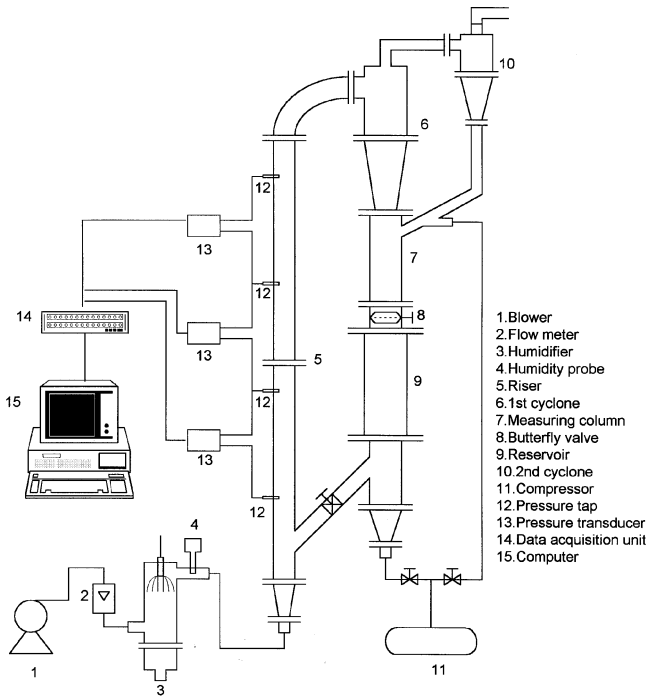

Fig. 1. Schematic diagram of experimental test facility.

In this study, the effects of coarse particles and the relative humidity of fluidizing air on the flow behavior of polymer particle-air suspension in the riser were investigated through the analysis of pressure drop fluctuations.

EXPERIMENTAL

A schematic diagram of the experimental apparatus employed in this study is illustrated in Fig. 1. The riser was made of a 5 cm I.D.×250 cm high acrylic pipe and four pressure taps were mounted along the bed height with the interval of 50 cm in order to measure the pressure drops at three different axial locations in the riser. Three differential pressure transducers were connected to pressure taps as shown in Fig. 1, and output voltage signals were stored by a PC through the data acquisition unit. The data sampling rate was 120 Hz and number of each sample per channel was 3000. The solid particles were separated from the gas by two cyclones connected in series at the top of the riser, and fed back to the bottom of the riser through a bubbling bed type particle reservoir. The particle feed rate to the riser was controlled by adjusting the opening of the gate valve and regulating the flow of fluidization air to the particle reservoir. The solid circulation rate (G_s) was measured by temporarily closing the butterfly valve located above the particle reservoir and timing the accumulation of a packed bed of solids along the return column. In order to examine the effect of relative humidity of fluidization gas, 7 cm I.D.×50 cm long humidifier was installed between the flowmeter and distributor of the riser. The fluidizing dry air was humidified by spraying the water from the nozzle at the top of humidifier. The relative humidity of air was controlled by changing the flowrate of water to the spray nozzle, and the relative humidity of air was monitored by a psychrometer.

Table 1. Physical properties of particles

	d_p (μm)	ρ_b (kg/m^3)	ρ_s (kg/m^3)	U_{mf}(m/s)	U_t(m/s)
PE	538	370	810	0.11	2.13
PVC	109	530	1100	0.0064	0.29
Glass bead	2000	1560	2500	2.61	11.32

The solid particles used in this experiment were 0.109 mm polyvinylchloride (PVC) and 0.530 mm polyethylene (PE) as fine particles, and 2.0 mm glass bead (GB) was employed as coarse particles. The physical properties of the employed particles along with the particle terminal velocities and the minimum fluidization velocities evaluated from the correlation are given in Table 1.

In the experiments with coarse particles, the coarse particles are introduced to the bed before the test run is started. Experiments were carried out in each case with and without 5 vol% coarse particles in various operating conditions at three different locations along the bed height (bottom zone: between 50 cm and 100 cm from the distributor, middle zone: between 100 cm and 150 cm, upper zone: between 150 cm and 200 cm).

DETERMINISTIC CHAOS ANALYSIS

1. Hurst Analysis

To analyze the nature of the chaotic motion like pressure fluctuation, rescaled range (R/S) analysis was proposed by Hurst in 1956 and later Mandelbrot and van Ness [1968] determined that R(t, τ)/S(t, τ) is a random function with a scaling relationship. Calculations of the Hurst exponent in this paper were obtained by Fan et al. [1993] and Kang et al. [1997].

Let $X^*(t)$ be a subset of pressure fluctuation signals from time t=to t=t.

$$X^*(t)=\sum_{n=0}^{t} X(u) \tag{1}$$

Then, the average of signals within the subrecord from time t+1 to time t+τ can be obtained.

$$\frac{1}{\tau}[X^*(t+\tau)-X^*(t)] \tag{2}$$

And let B(t, u) be the comulative departure from the mean for the subrecord between time t+1 and time t+τ.

$$B(t,u)=[X^*(t+u)-X^*(t)]-\left(\frac{u}{\tau}\right)[X^*(t+\tau)-X^*(t)] \tag{3}$$

The sample sequential range of X(t) for time delay τ is defined as

$$R(t,\ \tau)=\mathrm{Max}\ B(t,\ u)-\mathrm{Min}\ B(t,\ u)\ \ 0\le u\le\tau \tag{4}$$

and the sample sequential variance of X(t), $S^2(t, \tau)$ is defined as

$$S^2(t,\ \tau)=\frac{1}{\tau}\sum_{u=t+1}^{t+\tau} X^2(u)-\left[\frac{1}{\tau}\sum_{u=t+1}^{t+\tau} X(t)\right]^2 \tag{5}$$

The ratio, R(t, τ)/S(t, τ) is termed the rescaled range.

$$\frac{R(t,\ \tau)}{S(t,\ \tau)} \propto \tau^{H} \tag{6}$$

The Hurst exponent is the slope of log(R/S) vs fog τ plot and has been found to be >0.5 for independent random data.

2. Correlation Dimension

The correlation dimension of the attractor characterizes the spatial correlation between points on the attractor. The most common method of determining the correlation dimension, that of Grassberger and Procaccia [1984], was used in this study.

$$Z_i(t)=[X(i\cdot\Delta t),\ X(i\cdot\Delta t+\tau),\cdots,X(i\cdot\Delta t+(d-1)\tau] \tag{7}$$

where X(i) is the measured pressure fluctuation signals, τ is the time delay for attractor reconstruction, and d is the embedding dimension in phase space. Correlation integral, C(r) is defined as the cumulative probability distribution that two points on the attractor, $Z_i(t)$ and $Z_j(t)$ are within a arbitrary distance between two points, r

$$\begin{aligned} C(r) &= \lim_{m\to\infty}\frac{1}{m^2}[\text{number of pairs}(i,\ j)\ \text{whose distance} \\ &\quad |Z_i(t)-Z_j(t)|<r] \\ &= \lim_{m\to\infty}\frac{1}{m^2}\sum_{i=1}^{m}\sum_{j=1}^{m} H[r-|Z_i(t)-Z_j(t)|] \end{aligned} \tag{8}$$

where H is the Heaviside function

$$H[r-|Z(t)-Z(t)|]=\begin{cases}1 & \text{if } r>|Z_i(t)-Z_j(t)| \\ 0 & \text{otherwise}\end{cases} \tag{9}$$

The correlation dimension is related to the correlation integral C(r) and the distance r between two points on the attractor.

$$C(r)=r^{D} \tag{10}$$

The slope would be correlation dimension in a log C(r) vs log r plot in an embedding space of sufficient dimension. Correlation dimension is the dimension of the true state space or number of dynamical degree of freedom of the system. Therefore, it can be employed to estimate the minimum degree of freedom necessary to describe the systems [Bai et al., 1997].

RESULTS AND DISCUSSION

1. The Effect of Coarse Particles

The measured time series of pressure drop fluctuations at the upper zone of the riser as a function of gas velocity are plotted in Fig. 2, which shows that the pressure fluctuation decreased with gas velocity with and without coarse particles. These results indicated that the homogeneity of gas-solids flow increased with gas velocity and can be explained as that the increase of gas velocity significantly decreases the number of large size clusters [Wei et al., 1994]. Note that under the same operating conditions, the addition of coarse particles (glass beads) in the riser of PVC particles as shown in Fig. 2(b) reduced the pressure drop fluctuation compared to that of PVC particles only. Also, at the higher gas velocity, the reduction of pressure fluctuation was greater, since at the higher gas velocity, the movement of coarse particle is more vigorous, thus acting as the baffle for disintegrating the clusters. The same

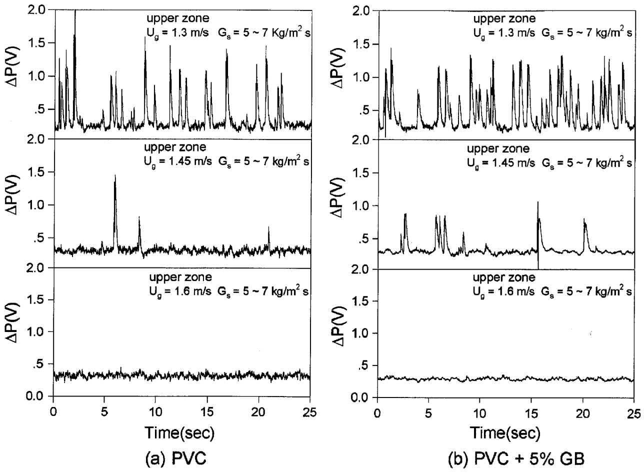

Fig. 2. Pressure fluctuation signals with different gas velocity (a) for PVC and (b) PVC+5% GB.

pressure fluctuation data employed in Fig. 2 was plotted by the so called the rescaled range analysis method and shown in Fig. 3. The Hurst exponent determined from the slope of the graph can be an index of quality of fluidization. The quality of fluidization in the riser with and without coarse particles can be determined quantitatively by comparing the magnitude of the Hurst exponent. By comparing the qualitative information of fluidization quality as seen in Fig. 2, it can be concluded that the higher value of Hurst exponent represented the lower pressure fluctuations because of more uniform flow of suspension in the riser. As shown in Fig. 3(a), (b) and (c), the Hurst exponent increased toward the top of the bed where the gas-solids flow is more uniform. Jiang et al. [1994] reported that the addition of coarse particles to the polyethylene particle enhanced the uniformity of the gas-solid flow, thus improving the quality of fluidization as demonstrated by the reduction of pressure drop fluctuations. The visualization of pressure fluctuation data in phase space trajectories also gives some qualitative information about the physical motion of a gas-solid flow system. The effect of solid circulation rates on the flow behavior is illustrated in Fig. 4(a) for polyethylene powder and Fig. 4(b) for polyethylene and coarse particles. As shown in Fig. 4(a) and 4(b) the size of the attractor increased with solid circulation rate. This may be due to the fact that the increased number of particles increased the interactions between particle-particle and particle-wall, thus increasing the probability of the formation of clusters. Bai et al. [1996] also reported that the increase in the solid circulation rate would increase the heterogeneity due to the formation of large clusters from the calculation of the fractal dimension. It can be also observed that the size of the attractor with coarse particles was smaller than that without the coarse particles. This qualitative comparison of the phase space trajectories indicated that the gas-solid flow with coarse particles is a more periodic and regular flow pattern by preventing the formation of aggregation in the riser.

The effect of solid circulation rate on the flow behavior of PE particles is given in Fig. 5. The Hurst exponents determined by the pressure drop fluctuations were plotted as a function of solid circulation rate. As can be seen in Fig. 5, the Hurst ex-

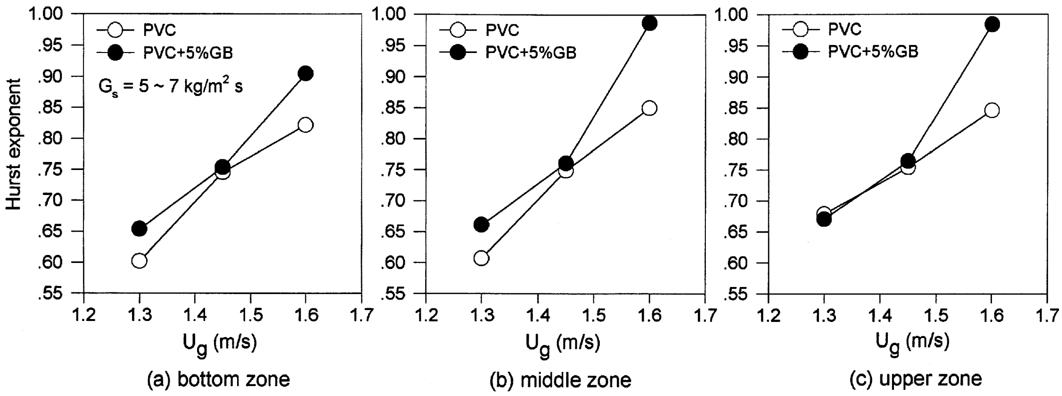

Fig. 3. The variations of Hurst exponent with gas velocity and coarse particle for (a) the bottom region, (b) the middle region, and (c) the upper region.

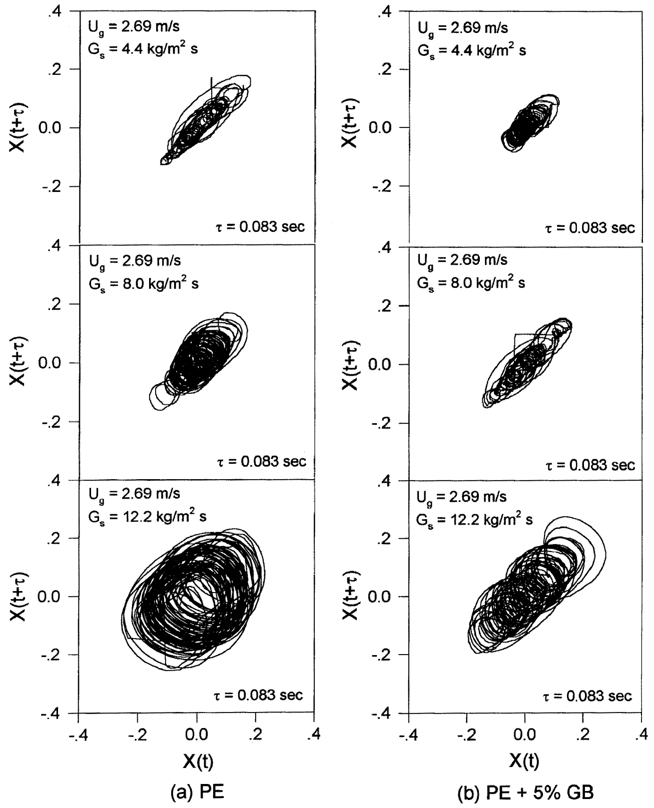

Fig. 4. The space-state trajectories with solid circulation rate for (a) PE and (b) PE+5% GB.

ponent decreased with the solid circulation rate. It is believed that the increase in the solid circulation rate results in the enhancement of the particle clustering. From Fig. 5, the effect of coarse particles on the flow behavior of PE particles was also observed. The addition of coarse particles to the bed of fine PE particles increased the Hurst exponent, which implies a reduction of the pressure fluctuations at the same operating conditions. Jiang et al. [1994] reported that collisions between fine particle clusters and coarse particles impede the formation of large clusters and hence improve operational stability. From the above-mentioned analysis of pressure drop fluctuations, it can be said that the deterministic chaos analysis of pressure fluctuation signals can be a good measure of gas-solid contact or fluidization quality in a circulating fluidized bed.

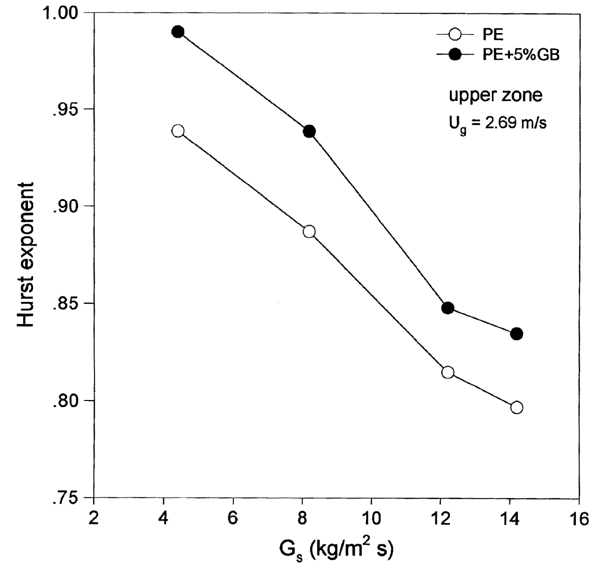

Fig. 5. The variation of Hurst exponent with solid circulation rate at the upper region.

2. The Effect of Relative Humidity

It is a well known fact that polyethylene particles possess a strong tendency to agglomerate and form larger clusters due to their high surface resistivity. This electrostatic charge effect may cause the more frequent formation of clusters in contrast to FCC particles. The presence of clusters of different sizes resulted in the non-uniform structure of gas-solid flow and chaotic motion in the riser. Wolny and Kazmierczak [1989] found that the electrostatic dissipation of polystyrene particles occurred with the fluidizing air of relative humidity of 70%. Jiang et al. [1997] also pointed out that the electrostatic charge for polyethylene particles decreased with the increasing air humidity. Fig. 6 shows the probability density function of pressure fluctuation for PVC particles in the upper zone of the riser. As can be seen in Fig. 6, a narrower band of pressure drop fluctuation was observed at the higher relative humidity of the fluidization air. This narrower band of pressure fluctuation at higher relative humidity means that the two-phase flow in the riser was

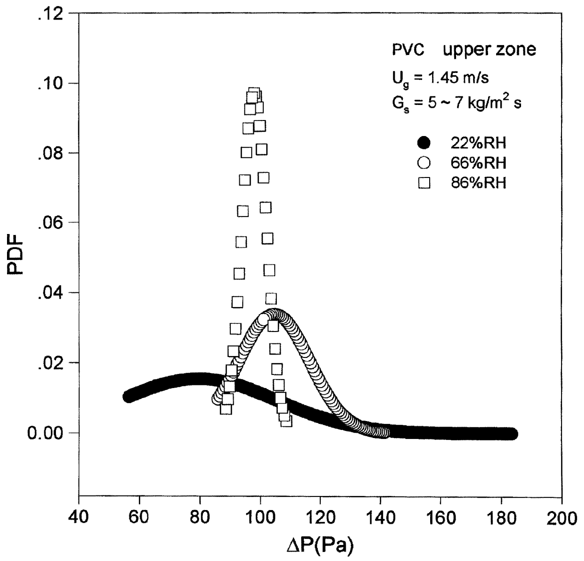

Fig. 6. The probability density function of pressure drop with relative humidity of air for PVC.

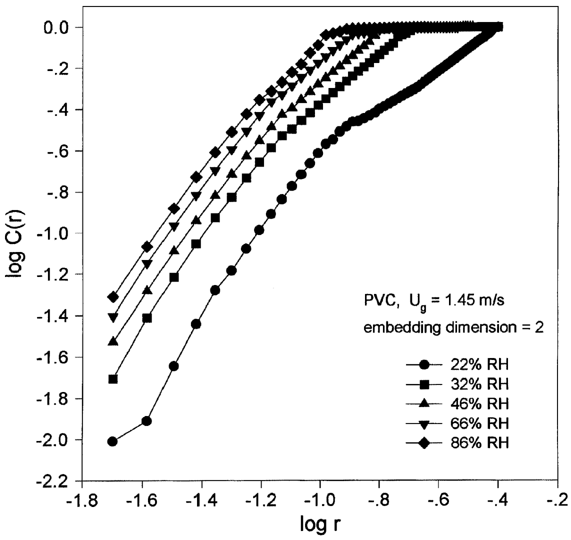

Fig. 8. Correlation integrals with relative humidity of air for PVC.

more homogeneous at higher humidity condition and it also implied the significance of humidity on the pressure drop fluctuations. Fig. 7 shows the Hurst exponent of pressure fluctuation as a function of relative humidity for PVC particles at three different axial locations. The Hurst exponent increased with relative humidity, and it is known fact that a higher value of the Hurst exponent implies that time-dependent behavior of pressure fluctuation in time series is persistent. Therefore, the flow is homogeneous at higher humidity, and it was also found that the flow fluctuations at the bottom zone of the riser were more random than that of upper zone at the same relative humidity. The correlation integrals with different relative humidity for PVC particles are shown in Fig. 8 for small radii (between −1.8 and −0.4) for the determination of correlation dimension. The invariant slope is the correlation dimension and it represents the characteristics of the particle motion. The correlation dimension at three different axial locations as a function of relative humidity is shown in Fig. 9. As shown in Fig. 9, the correlation dimensions decreased with relative humidity and axial height. The correlation dimension of a total periodic motion is one and the obtained correlation dimensions for PE particles was found as 1.5 to 2.5 for the motion of particles. These correlation dimensions of 1.5 to 2.5 are higher than that of Bouillard and Miller [1994]. They employed the 0.075 mm FCC particles and obtained the correlation dimension of 1.5 and 1.8 for upper section and lower section of the riser, respectively. Therefore, a simple comparison of the magnitude of correlation dimensions for PVC and FCC particles indicated that it is more difficult to describe the flow behavior of a circulating fluidized bed with polymer particles.

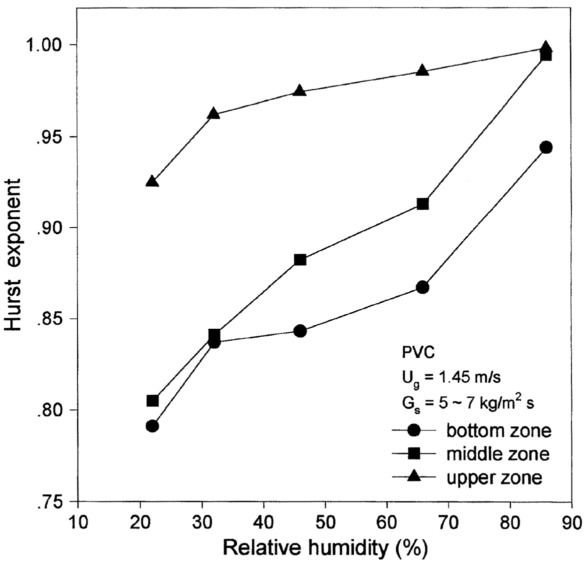

Fig. 7. The variation of Hurst exponent with relative humidity of air for PVC.

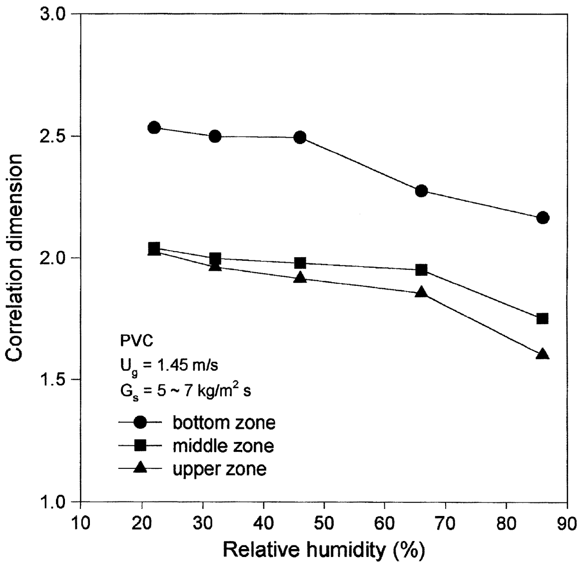

Fig. 9. Correlation dimension with relative humidity and axial location for PVC.

CONCLUSION

The pressure fluctuations along the height of the riser and the effect of coarse particles and humidity of air on the flow behavior have been analyzed in terms of deterministic chaos theory, and the following conclusions were obtained.

1. The heterogeneity of gas-solid flow in the riser was influenced by the gas velocity, the solid recycle rate and the bed height. The flow structure of the dense lower region and dilute upper region was observed from the measurement of pressure drop fluctuations.

2. The addition of coarse particles to fine polymeric particles increased the Hurst exponent; this means that the time dependent behavior of pressure drop fluctuation is persistent due to prevention of the formation of clusters.

3. The higher humidity of fluidizing air reduced the electrostatic charges of polymeric particles, thus increasing the homogeneity of gas-solid flow.

4. The application of deterministic chaos theory of the pressure fluctuation signals could be a useful measure for describing the flow behavior in a circulating fluidized bed.

ACKNOWLEDGMENT

The authors are grateful to the Korea Science and Engineering Foundation for the financial support.

NOMENCLATURE

B(t, u) : accumulated departure from the mean value
D : correlation dimension
d : mension of the reconstructed vector or embedding dimension
G_s : solids circulation rate [kg/m^2 s]
H : hurst exponent
m : total number of points used for calculation of correlation integral
P : pressure drop [Pa]
$\overline{P}$: mean pressure drop [Pa]
$R(t, \tau)$: sample sequential range for τ
r : arbitrary distance between two points
$S^2(t, \tau)$: sample sequential variance
U_g : superficial gas velocity [m/s]
X(u) : pressure fluctuation signal
$X^*(t)$: subset of pressure fluctuation signals
Z(t) : reconstructed phase space vector

Greek Letters

τ : time delay [sec]
σ : standard deviation [Pa]

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