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Particle Flow Behavior in Three-Phase Fluidized Beds

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Abstract−Non-uniform flow behavior of fluidized solid particles in three-phase fluidized beds has been analyzed by adopting the stochastic method. More specifically, pressure fluctuation signals from three-phase fluidized beds (0.152 m ID × 2.5 m in height) have been analyzed by resorting to fractal and spectral analysis. Effects of gas flow rate (0.01-0.07 m/s), liquid flow rate (0.06-0.18 m/s) and particle size (0.001-0.006 m) on the characteristics of the Hurst exponent, spectral exponent and Shannon entropy of pressure fluctuations have been investigated. The Hurst exponent and spectral exponent of pressure fluctuations attained their local maxima with the variation of liquid flow rate. The Shannon entropy of pressure fluctuation data, however, attained its local minima with the variation of liquid flow rate. The flow transition of fluidized solid particles was detected conveniently by means of the variations of the Hurst exponent, spectral exponent and Shannon entropy of pressure fluctuations in the beds. The flow behavior resulting from multiphase contact in three-phase fluidized beds appeared to be persistent and can be characterized as a higher order deterministic chaos.

Key words: Three Phase Fluidized Beds, Stochastic Analysis, Pressure Fluctuations, Hurst Exponent, Shannon Entropy, Spectral Exponent, Flow Transition of Particles

INTRODUCTION

Various attempts have been made to analyze the hydrodynamic characteristics of three-phase fluidized beds because of the increasing demands of their applications. Since the solid particles exist as a dispersed phase in three-phase fluidized beds, the flow behavior and flow regime of the particles have been recognized as important factors in determining the performance of three-phase fluidized bed reactors and contactors [Epstein, 1983; Fan, 1989; Kim and Kang, 1996, 1997]. The bubble motion and its characteristics can be influenced strongly by the flow behavior of fluidized solid particles, since the particles would have bubble breaking potential [Fan et al., 1987; Kang et al., 1992, 1997]. Nevertheless, relatively little attention has been focused on the particle flow behavior in three-phase fluidized beds. It has been reported that the rates of heat and mass transfer, particle dispersion rate and radial dispersion coefficient of a liquid phase exhibit their maximum values with the variation of liquid flow rate and bed porosity in three-phase fluidized beds [Fan, 1989; Kim and Kang, 1997]. These phenomena can be related to the flow motion and flow regime transition of fluidized solid particles, because the bed height of the three-phase bed is determined by the expanded height of the fluidized particles existing as a batchwise dispersed phase in the bed [Kang et al., 1988, 1997].

In the present study, particle flow behavior has been investigated by adopting the stochastic method. More specifically, the Hurst exponent, spectral exponent and Shannon entropy of the pressure fluctuations in the bed have been utilized to express the characteristics of the flow behavior and transition of solid particles as a quantitative expression or a parameter.

ANALYSIS

1. Hurst Exponent

For a given time series of recorded pressure fluctuations, X(t), spaced in time from t=1 to t=T, X*(t) can be defined as [Fan et al., 1990; Yashima et al., 1992; Kang et al., 1995, 1996; Kwon et al., 1995]

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

Then, the average of recorded signals within the subrecord from time t+1 to time t+τ is

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

This average is equivalent to the slope between X*(t) and X*(t+τ). Let B(t, u) denote the cumulative departure of X(t+u) from the average for the subrecord between time t+1 and time t+τ; note that by definition,

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

The sample sequential range, R(t, τ) is defined as

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

Let $S^2(t, \tau)$ be a sample sequential variance of the subrecord from time t+1 to time t+τ.

Then,

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

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The ratio, R(t, τ)/S(t, τ), which is termed the rescaled range, has been found to scale as a power function of τ, i.e.,

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

If it is a random function and is self-affine, this time series exhibits a long-term correlation when 0.5<H<1.0.

The value of the Hurst exponent, H, can be evaluated from the log-log plot of R/S against time lag. For each time lag, the rescaled range (R/S) has been computed for five different starting times; this is evident from the presence of five data points, some of which are overlapping, at each lag. The local fractal dimension, d_{FL}, of the fluctuating signal of a fractional Brownian motion has been defined in terms of the Hurst exponent.

2. Spectral Exponent [Priestler, 1981; Schumwang, 1988; Hillborn, 1994]

The power spectra of pressure fluctuation time series, X(t), can be homogeneous power functions of the form $f^{-\alpha}$ over some respectable range of frequencies, with the exponent α.

Such homogeneous spectra can exhibit a simple scaling invariance, that is to say, if such a process is compressed by a constant scale factor s, then the corresponding Fourier spectrum is expanded by the reciprocal factor 1/s. However, changing the frequency scale by any constant factor does not change the frequency dependence for power-law spectra; they keep their form. Thus, such spectra are self-similar and the underlying processes are statistically self-similar of self-affine.

3. Shannon Entropy [Priestler, 1981; Schumwang, 1988; Hillborn, 1994]

The Shannon entropy can be utilized to express the degree of uncertainty in being able to predict the output of a probabilistic event. If the data has r possible outcomes whose probabilities are P_1, P_2, ... P_r, then the Shannon entropy can be obtained by

$$H_S = \sum_{i=1}^{r} P_i \ln\frac{1}{P_i} \qquad (7)$$

EXPERIMENT

Experiments were carried out in an acryl column of 0.152 m in ID and 2.5 m in height (Fig. 1). The detailed experimental apparatus can be found elsewhere [Kang et al., 1997]. Water and glass beads whose density is 2,500 kg/m^3 were used as a liquid and a fluidized particle, respectively. The particle size was in the range from 1.0×10^{-3} to 6.0×10^{-3} m in diameter. The liquid flow rate, which was regulated by two valves and measured by a rotameter, was in the range of 0.06-0.18 m/s and that of gas was 0.01-0.07 m/s.

Pressure fluctuations and their histograms were measured and recorded by a recorder and a personal computer after amplifying and converting the signals from the pressure sensor. The pressure sensor was a semiconductor type, which was fast enough to follow the dynamic fluctuations of pressure in the bed.

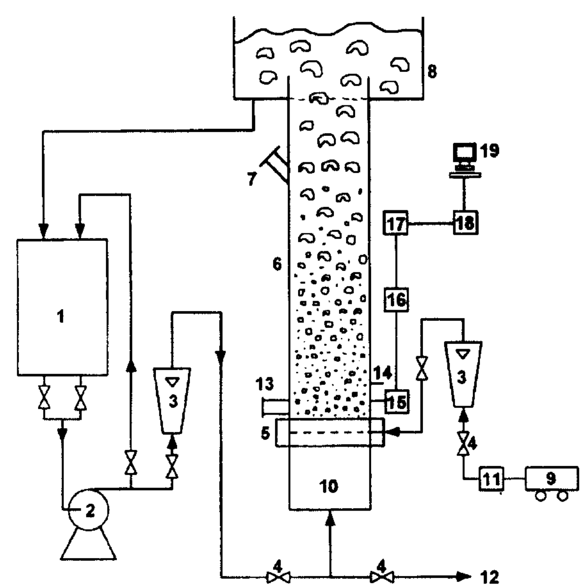

Fig. 1. Schematic diagram of experimental apparatus.

1. Reservoir	11. Filter & regulator
2. Pump	12. Drain
3. Rotameter	13. Solid discharge
4. Valve	14. Pressure taps
5. Distributor	15. Pressure transducer
6. Main column	16. Oscilloscope
7. Loading port	17. Filter
8. Weir	18. A/D converter
9. Compressor	19. Computer
10. Calming section	

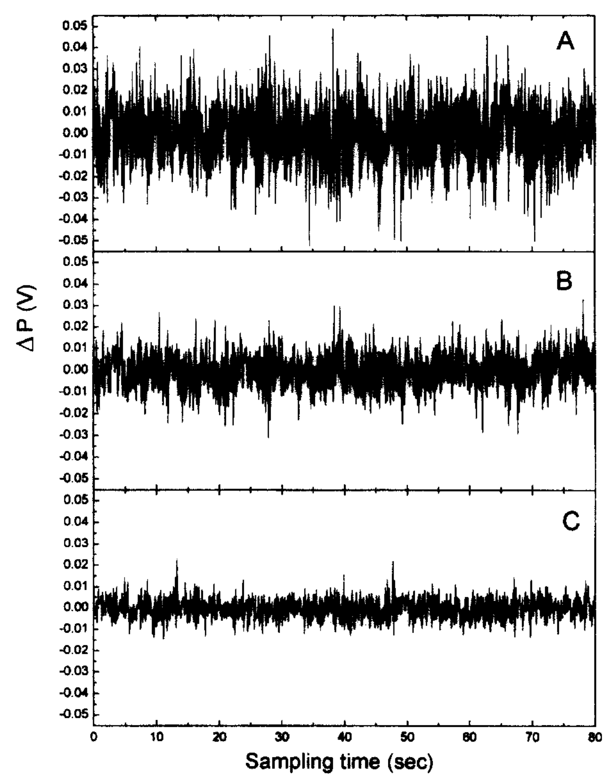

Fig. 2. Typical pressure fluctuation signals at the steady state in three-phase fluidized beds (dp=1 mm, U_G=0.03 m/s).

	A	B	C
U_L [m/s]	0.06	0.08	0.10

The sensor was located 0.1 m and 0.2 m above the distributor. Effects of pressure sensor location on the axial dispersion coefficient of the particles have been known to be negligible [Kang et al., 1992].

The voltage-time signal, corresponding to the pressure-time signal, from the pressure transducer was fed to the recording system at selected sampling rate of 0.032 sec. A typical sample comprised 3,000 points. This combination of the sampling rate and sample length ensured capturing of the full spectrum of hydrodynamic signals from the three phase fluidized bed at steady state operating condition.

RESULTS AND DISCUSSION

Typical pressure fluctuation signals can be seen in Fig. 2 with the variation of liquid flow rate. The measured pressure fluctuations have been treated by the rescaled range analysis. The resultant rescaled range correlates almost linearly with the time lag, τ, as can be seen in Fig. 3. The individual value of the Hurst exponent (H) has been recovered from this Pox diagram with a correlation coefficient greater than 0.95 for all the data recorded.

Fig. 4 shows the variation of H with an increase in the liquid flow rate. As can be seen in this figure, the Hurst exponent exhibits its maximum value with an increase in the liquid flow rate in all the cases studied. In other words, the pressure fluctuations in three-phase beds would be more periodic rather than stochastic at the intermediate liquid flow rate. This can imply that the flow structure of three-phase fluidized beds would be more persistent at the intermediate liquid flow rate condition [Kang and Kim, 1988]. It has been generally understood that the bubble properties and holdup cannot be influenced significantly with the variation of liquid flow rate in the bubble column.

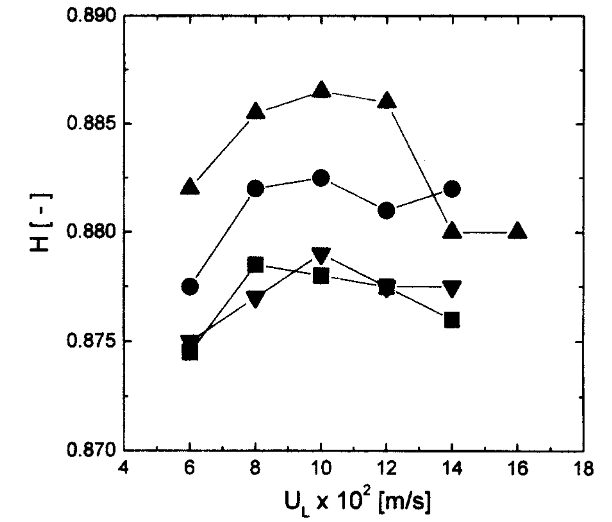

Fig. 4. Effects of U_L on H of pressure fluctuations in three-phase-fluidized beds (U_G=0.03 m/s).

	■	●	▲	▼
dp [mm]	1	3	6	3
h [m]	0.20	0.10	0.10	0.20

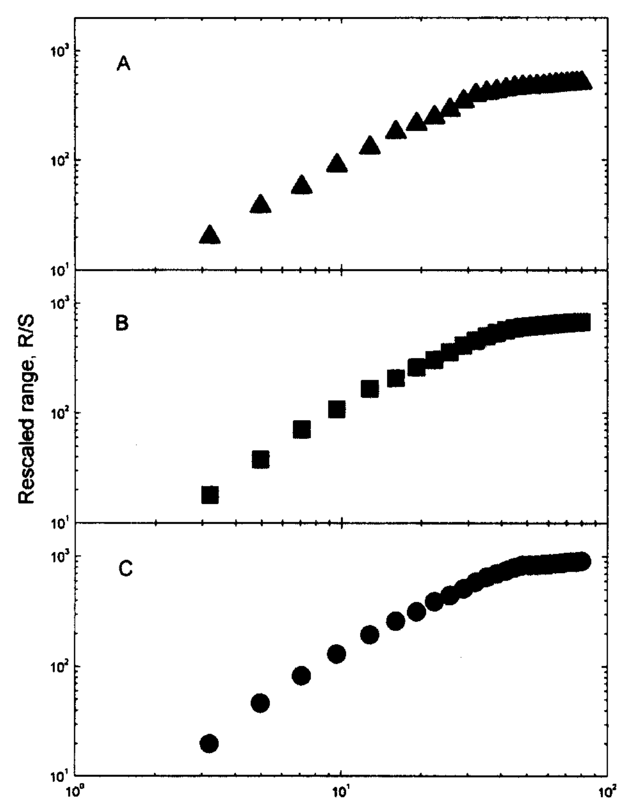

Fig. 3. Typical Pox diagram from the rescaled range analysis of pressure fluctuations in three-phase fluidized beds (dp=1 mm, U_G=0.03 m/s).

	A	B	C
U_L [m/s]	0.06	0.08	0.10

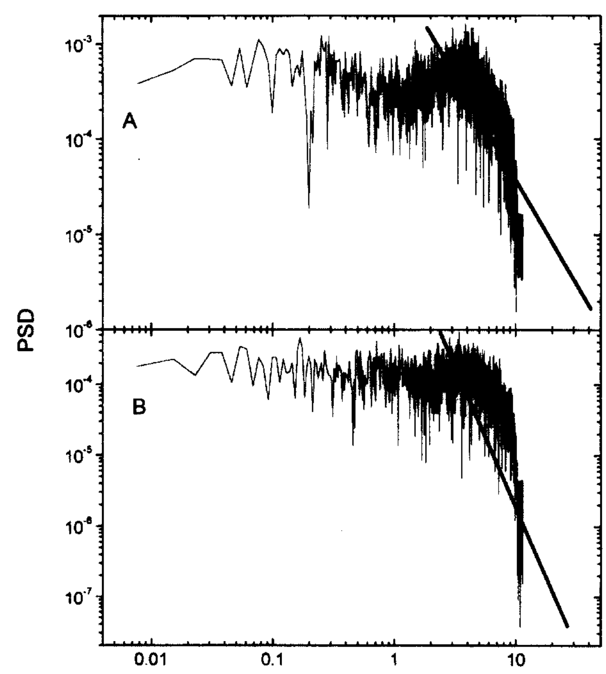

Fig. 5. Typical power spectra of pressure fluctuations in three-phase fluidized beds (dp=3 mm, U_G=0.07 m/s).

	A	B
U_L [m/s]	0.06	0.10

However, in three-phase fluidized beds, the bubble properties and gas holdup are frequently influenced by the liquid flow rate [Kang et al., 1988, 1991]. This can be due to the fluidized solid particles possibly playing a fatal role for the determination of the multiphase flow behavior in three-phase fluidized beds.

Fig. 5 shows the power spectral density function obtained from the pressure fluctuations in three-phase fluidized beds. The spectral exponent, α, has been recovered from this log-log plot of power spectra. As can be seen in Fig. 6, the spectral exponent exhibits its maximum value with an increase in the liquid flow rate. Because a higher value of the spectral exponent means higher self-similarity or self-affineness of the underlying process [Hillborn, 1994], the flow structure of the three phase fluidized beds would be better self-similar or self-affine at the intermediate liquid flow rate condition. The self-similarity of the pressure fluctuation signals can be corresponding to the persistence of the signals.

Fig. 7 shows the effects of liquid flow rate on the Shannon entropy of pressure fluctuation in three-phase fluidized beds. Note in this figure that the Shannon entropy, H_s, goes through a minimum point with an increase in the liquid flow rate in all the cases studied. Since the increase of Shannon entropy is related to the increase of uncertainty of having more possible equal probability events, the lower value of H_s is corresponding to the increase of certainty that an event would occur. That is, lower Shannon entropy means the higher probability to anticipate that an event would occur. If the pressure fluctuation signals would be composed of two components, periodic and stochastic components, the periodic component would be more predictable than the stochastic one at the condition of a relative low value of H_s of pressure fluctuations. Thus, it can be stated that the lower value of H_s is related to the more periodicity of the signals and thus to their self-similarity.

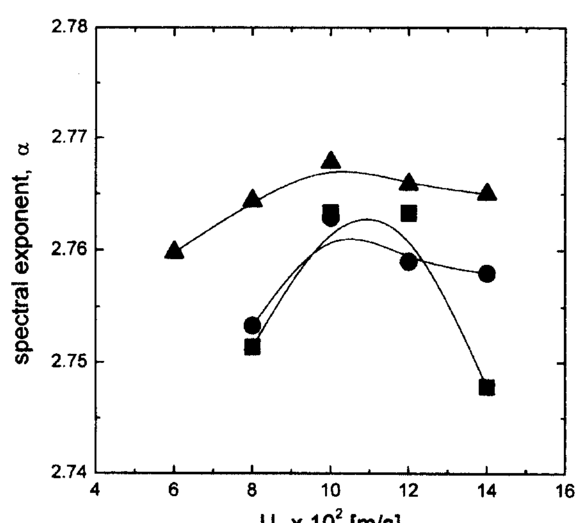

Fig. 6. Effects of U_L on α of pressure fluctuations in three-phase fluidized beds (U_G=0.03 m/s).

	■	●	▲
dp [mm]	1	3	3
h [m]	0.10	0.20	0.10

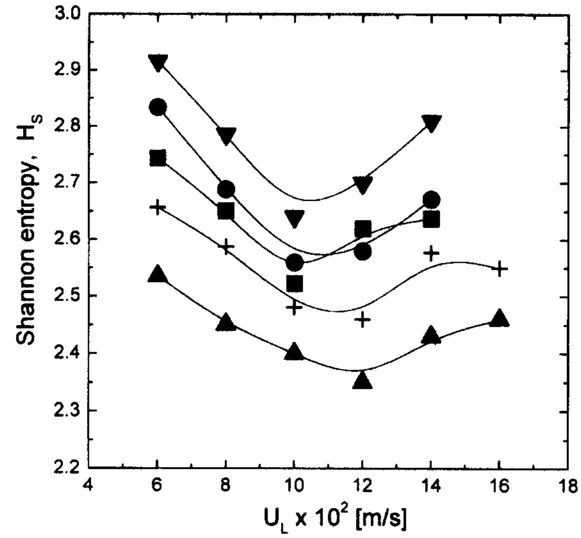

Fig. 7. Effects of U_L on H_s of pressure fluctuations in three-phase fluidized beds (U_G=0.03 m/s).

	■	●	▲	▼	+
dp [mm]	1	3	6	1	6
h [m]	0.10	0.10	0.10	0.20	0.20

In three-phase fluidized beds, the solid particles are fluidized mainly by means of upward liquid flow; thus, the motion or behavior of particles would be primarily influenced by the liquid flow rate [Kang and Kim, 1988]. Thus, it is highly plausible that the flow structure and behavior of fluidized particles would be quite different at the lower liquid flow rate from these when the liquid flow rate is high. This can lead us to state that the flow regime of fluidized particles would be changed at the intermediate liquid flow rate condition, and that the persistence, self-similarity and predictability of the flow behavior are maximum at that liquid flow rate condition. The motion of individual particles is constrained by the neighboring particles at low liquid flow rate. The particles tend to move in groups or in clusters at low liquid flow rate. Nevertheless, the particles tend to move individually and randomly when the liquid flow rate is elevated to an intermediate level. Under these intermediate conditions, the particles oscillate locally in relatively narrow ranges of frequency and amplitude. However, the turbulent random motion of individual particles becomes dominant and the decrease of solid holdup becomes significant at the higher liquid flow rate. At this intermediate liquid flow rate, the transfer coefficient (mass or heat transfer coefficient) has a maximum value [Kang et al., 1996; Kim and Kang, 1997].

CONCLUSION

1. The non-uniform flow behavior and flow transition of fluidized particles have been analyzed effectively by means of a stochastic analysis of pressure fluctuations in three-phase fluidized beds.

2. The Hurst exponent and spectral exponent of the pressure fluctuations exhibited their maxima, whereas the Shannon entropy of them attained its minimum, with the variation of liquid flow rate in three-phase fluidized beds.

3. The flow regime transition of fluidized particles would occur at the intermediate liquid flow rate where the H and α of pressure fluctuations attained their maxima and the H_s exhibited its minimum in three-phase fluidized beds.

NOMENCLATURE

f : frequency [Hz]
H : Hurst exponent
H_S : Shannon entropy
PSD : power spectral density of X(t)
P_i : probability density function
R(t, τ) : sample sequential rescaled range
$S^2(t, \tau)$: sample sequential variance
U_L : liquid flow rate [m/s]
X(t) : pressure fluctuation time series [v]
X*(t) : subset of time series [v]

Greek Letters

τ : time lag
α : spectral exponent

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