Particle Flow Behavior in Three-Phase Fluidized Beds

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(Received 2 April 1999 • accepted 9 July 1999)

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 x 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]

\[
X^*(t) = \sum_{u=1}^{t} X(u)
\]

Then, the average of recorded signals within the subrecord from time \( t+1 \) to time \( t+x \) is

\[
\frac{1}{x} \left[ X^*(t+x) - X^*(t) \right]
\]

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

\[
B(t, u) = \left[ X^*(t+u) - X^*(t) \right] - \left[ X^*(t+1) - X^*(t) \right]
\]

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

\[
R(t, x) = \max \left[ B(t, u) \right] - \min \left[ B(t, u) \right]
\]

Let \( S'(t, \tau) \) be a sample sequential variance of the subrecord from time \( t+1 \) to time \( t+\tau \).

Then,

\[
S'(t, \tau) = \frac{1}{\tau} \sum_{u=t+1}^{t+\tau} X'(u) - \left[ \frac{1}{\tau} \sum_{u=t+1}^{t+\tau} X(u) \right]^2
\]

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The ratio, \( \frac{R(t, \tau)}{S(t, \tau)} \), which is termed the rescaled range, has been found to scale as a power function of \( \tau \), i.e.,

\[
\frac{R(t, \tau)}{S(t, \tau)} \propto \tau^{H(t)}
\]

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, \( d_F \), of the fluctuating signal of a fractional Brownian motion has been defined in terms of the Hurst exponent.


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 \( \alpha \).

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.


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 \( P_1, P_2, \ldots, P_r \), then the Shannon entropy can be obtained by

\[
H_s = \sum_{i=1}^{r} P_i \ln \frac{1}{P_i}
\]

**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/m³ were used as a liquid and a fluidized particle, respectively. The particle size was in the range from \( 1.0 \times 10^{-3} \) to \( 6.0 \times 10^{-3} \) 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.