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Study on the nature of pressure signals in a bubbling fluidized bed*

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Abstract: In this study on the nature of pressure signals generated by a deterministic or stochastic process in a bubbling fluidized bed, pressure fluctuation measurements were carried out in a 300-mm-diamet column at 0.090 m and 0.40 m above the distributor for different gas velocities. The method of detecting deterministic dynamic underlying pressure signals is proposed on the basis of predictability of pressure fluctuations. The deterministic nature of dynamics in fluidizing system was verified. The deterministic level of dynamics in fluidizing system was analyzed for different locations of pressure measurements and different gas velocities.

Key words: Nature, Pressure fluctuation, Deterministic dynamic, Predictability
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INTRODUCTION

Chaotic behavior is an interesting nonlinear phenomenon that had been intensively studied during the last two decades. Deterministic techniques have been used to gain understanding of the dynamical structure in many nonlinear systems. Particularly, the gas-solid two-phase flow systems present nonlinear dynamical behavior that can be studied by means of chaos criteria.

Knowledge of bed fluctuations in a gas-solids fluidized bed is important for its design and/or operation. Study of the essence of pressure fluctuations in fluidized beds is very helpful for understanding the complex hydrodynamic behavior of fluidized beds. Many investigators have studied the nature of pressure signals in different fluidized beds. Different views have been published for the nature of pressure fluctuations. Early studies showed that pressure fluctuations are periodic (Verloop et al., 1974) or that the signals of pressure fluctuations are composed of a random component following fBm (fractional Brownian motion) and one or more periodic components (Fan et al., 1990). Cai et al. (1988) thought that pressure signals are random after experimental investigation. Many researchers thought that pressure fluctuations are chaotic (Bai et al., 1997; Daw et al., 1990; Karamavruc et al., 1997; van den Bleek et al., 1993). One of important points in chaos theory is that random-looking aperiodic behavior may be the product of determinism. This led us to think that pressure fluctuations in fluidized beds do not stem from some stochastic process but from some deterministic mechanism.

Various invariants for analyzing pressure fluctuations have been proposed to characterize their complexity. For example, power spectra are particularly suitable for analysis of linear systems, where their interpretation is often transparent, whereas the dimension, Lyapunov exponent and Kolmogorov entropy have been used to study geometrical and temporal properties of chaotic dynamics. However, none of these measures can be readily applied directly to determine if the system dynamics to be studied are generated by a deterministic, rather than a stochastic, process (Kaplan et al., 1992). There has been great interest in the last years aimed to detect "determinism" in time series.

The chaotic property with sensitive dependence on initial conditions for pressure signals in a bubbling fluidized bed was verified by Zhao et al. (2000). The goal of the present work is to detect determinism underlying pressure fluctuations

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based on the predictability of pressure signals.

EXPERIMENTAL DETAILS

The experimental setup is showed in Fig. 1. The fluidized bed assembly includes a bed column, a distributor, and a plenum chamber. The bed is 0.3 m in diameter and 3 m in height.

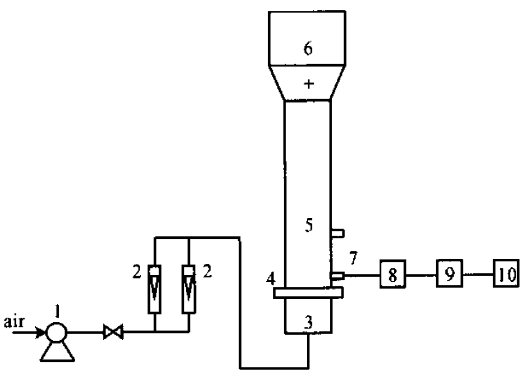

Fig. 1 Experimental setup.
1. blower; 2. rotameter; 3. plenum; 4. distributor; 5. bed; 6. disengaging section; 7. pressure probes; 8. pressure transducers; 9. A/D board; 10. computer.

Polyethylene particles were used as the fluidized particles. It had a density of 960 kg/m^3, and average diameter of 500 μm. Its minimum fluidized-gas velocity u_{mf} was 0.118 m/s, and static-bed height was 0.46 m. The fluidizing fluid was air. The distributor had 2 mm diameter holes and fractional open area was 4%. Four piezoresistive pressure transducers (CYG219 type, Baoji Research Center of Transducer, China) were used to measure local pressure fluctuations. Pressure probes were installed on the wall of the bed column at the level of 0.090 m, 0.20 m, 0.40 m above the distributor and 0.12 m below it, corresponding data run number was C1, C2, C3, C4 respectively. Each pressure probe was connected to one of the two input channels of differential pressure transducer, which produced an output voltage proportional to the pressure difference between the two channels. The remaining channel was exposed to the atmosphere. The differential range of the pressure transducer was ±4kPa, and the relative accuracy was ±0.1% full scale. The time series consisted of at least 60 000 points and were sampled at frequency of 250 Hz using an analog to digital converter with 12 bit nominal resolution. A low-pass filtering at 20 Hz was always applied off-line based on FFT before data analysis.

METHOD FOR DETECTING DETERMINISM

We can construct dynamical models in a number of different ways. One of the simplest methods works as follows. Suppose that the measured time series of discrete pressure fluctuations is p_1, p_2, p_3, …, p_N and its sample interval is $\Delta t = 1/f_s$. We want to make a predictive value of pressure at time $N+1$: P_{N+1}. (1) Embed the time series to produce X_i, the ith point in reconstructed phase space X_i($i=1, 2, \cdots, N_m$), where N_m is the number of point in reconstructed pseudo-state-space, $N_m = N-(m-1)\tau$; (2) Take the embedded point at time N_m, $X_{Nm} = (p_{Nm}, p_{Nm+\tau}, \cdots, p_N)$, and look through the rest of the embedded time series to find the point that is closest to X_{Nm}. If this closest point has time K_n, X_{Kn} is closer to X_{Nm} than any other X_i; (3) The definition of determinism is that future events are set causally by past events. X_{Nm} describes the past events to X_{Nm+1}. Similarly X_{Kn} describes the past events to the measurement X_{Kn+1}. If X_{Nm} is close to X_{Kn}, and if the system is deterministic, then we expect that X_{Kn+1} will be close to X_{Nm+1}. We assume that the reconstructed fluidizing dynamics can be described using some deterministic map (Zhao et al., 2000):

$$X_{n+1} = F(X_n) \tag{1}$$

where F: $R^m \rightarrow R^m$ is a map with $F=(f_1, f_2, \cdots, f_m)$ in reconstructed m-dimensional space. In fact, prediction of one point of the time series at next time P_{N+1} is prediction of one point in reconstructed m-dimensional space at next time X_{Nm+1}

$$X_{Nm+1} = (p_{Nm+1}, p_{Nm+\tau}, \cdots, p_{N+1})^{\mathrm{T}}$$

where, τ delay time of the embedding space,

$$\tau = k\Delta t$$

thus

$$P_{N+1} = f_m(X_{Nm}) = f_m(X_{Kn} + X_{Nm} - X_{Kn}) \tag{2}$$

Expanding the right side of Eq. (2) in a Talyor series about the fiducial point X_{Kn}, we have

$$P_{N+1} = f_m(X_{Kn}) + \sum_{i=1}^{m} \frac{\partial f_m}{\partial x_i(Kn)}(x_i(Nm) - x_i(Kn)) + \sum_{i=1}^{m}\sum_{j=1}^{m} \frac{\partial^2 f_m}{\partial x_i(Kn)\partial x_j(Kn)}(x_i(N_m) - x_i(Kn))(x_j(Nm) - x_j(Kn)) + \cdots \quad (3)$$

where $x_i(j) = p_{j+(i-1)\tau}$ and $f_m(X_{Kn}) = p_{Kn+1}$ can be measured by experiment, so Eq. (3) becomes:

$$P_{N+1} = p_{Kn+1} + Df_{m\beta}(x_\beta(N_m) - x_\beta(Kn)) + D^2 f_{m\beta\zeta}(x_\beta(N_m) - x_\beta(Kn))(x_\zeta(N_m) - x_\zeta(Kn)) + \cdots \quad (4)$$

where

$$Df_{m\beta} = \frac{\partial f_m}{\partial x_\beta(Kn)},\ D^2 f_{m\beta\zeta} = \frac{\partial^2 f_m}{2!\ \partial x_\beta(Kn)\partial x_\zeta(Kn)},\ \cdots \quad (\beta, \zeta = 1, 2, \cdots, m) \quad (5)$$

However, $Df_{m\beta}$, $D^2 f_{m\beta\zeta}$, $(\beta, \zeta = 1, 2, \cdots, m)$ at time Kn can be solved by a least-squares method presented by Eckmann et al. (1986). Repeating the above process according to predictive P_{N+1}, the time series of pressure fluctuations can be predicted. As Kaplan and Glass (Kaplan and Glass, 1995) proposed, there are two ways to predict. One is to use the model to predict the value at time $N+1$. Then we construct a new embedded point using this predicted value P_{N+1}:

$$X_{Nm+1} = p_{Nm+1},\ p_{Nm+1+\tau},\ p_{Nm+1+2\tau},\ \cdots, P_{N+1})^{\mathrm{T}} \quad (6)$$

We then find the nearest points to X_{Nm+1} to make a prediction of the value at time $N+2$, which we call P_{N+2}. This process can be iterated, that is, we use past predictions to make future predictions. Zhao et al. (2000) used this way to study the long-term unpredictability of pressure fluctuations in a bubbling fluidized bed. However, for the purposes of assessing determinism in data it is better to use the measured data directly. In this second way of making predictions, in order to predict the value at time $N+2$, we make the embedded point

$$X_{Nm+1} = (p_{Nm+1},\ p_{Nm+1+\tau},\ p_{Nm+1+2\tau},\ \cdots,\ p_{N+1})^{\mathrm{T}} \quad (7)$$

Note that here the measurement at time $N+1$ is used, and not the prediction P_{N+1}; we are not using the past predictions to make future predictions.

Once predictions have been made, we can calculate a mean prediction error ε:

$$\varepsilon = \frac{1}{N}\sum_{k=1}^{N}(p_{N+k} - P_{N+k})^2 \quad (8)$$

Very large ε means the predictions are bad and the system is not deterministic. Conversely, small ε suggests that the system is deterministic. A convenient way to decide if ε is large or small is to compare it to the variance of the time series σ^2. We can do this by taking the ratio ε/σ^2. If this ratio is close to one, then the mean prediction error is large. If the ratio is close to zero, then the mean prediction error is small and the fluidizing system is deterministic.

RESULTS AND DISCUSSION

Takens (1981) showed with regard to reconstruction that if the dimension of the manifold containing the underlying attractor is d, then embedding the data in a dimension $m \geqslant 2d+1$ preserves the topological properties of the attractor. Our study showed that the measured pressure signals are those of a low dimension hydrodynamic attractor, whose dimension varied between 1.1 and 1.5 over the range of gas velocities studied by means of computing the correlation dimension using Grassberger-Procaccia's algorithm (Grassberger and Procaccia, 1983). Similar results were abtained by Bouillard and Miller (1994). So embedding dimension $m = 3$ will be used in the following study.

We chose time delay τ as embedding when a two-dimensional phase portrait plotted by $p(t+\tau)$ against $p(t)$ is geometrically similar to the plots $\mathrm{d}p(t)/\mathrm{d}t$ versus $p(t)$. As shown in Fig. 2, the trajectories of (Fig. 2c) show more similarities to the phase space trajectories constructed in (Fig. 2a) than the trajectories in (Fig. 2b) and (Fig. 2d). Therefore, the embedding time delay $\tau = 8\Delta t$ was taken.

Comparison between the measured value and predicted value of pressure signals and their mean prediction error ε/σ^2 are shown in Fig. 3 at $u = 0.405$ m/s. Here the ratio ε/σ^2 is far from unity

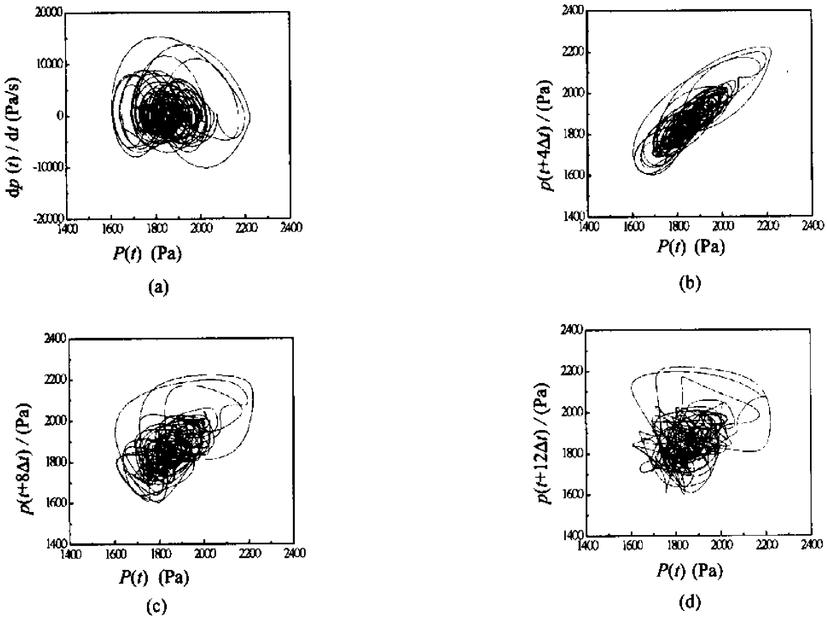

Fig. 2 **Phase space construction of the pressure data at $u = 0.231$m/s (a); and pseudo phase space constructions of the pressure data using $\tau = 4\Delta t$ (b); $\tau = 8\Delta t$ (c) and $\tau = 12\Delta t$ (d).**

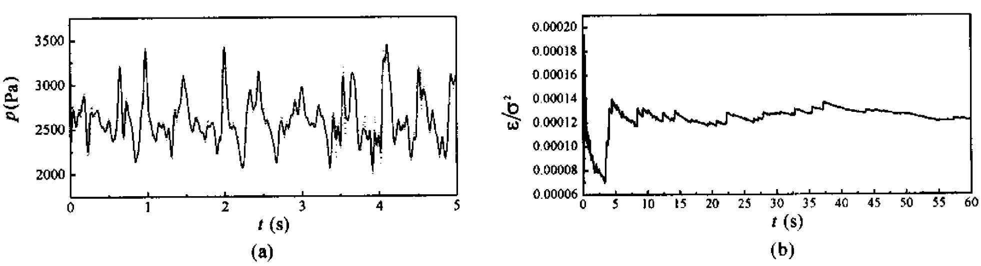

Fig. 3 **Comparison between a measured value and a predicted value of pressure signal (a); Their mean prediction error ε/σ^2 at $u = 0.405$m/s (b)**

——measured pressure signal; ······ predicted pressure signal

and tend to stability with time. So we can conclude that dynamics of the fluidizing system is deterministic.

The mean prediction error ε/σ^2 of pressure signals measured at two different axial heights distance from the distributor 0.090 m and 0.40 m for different gas velocities is shown in Fig. 4. It is clear that the ratio ε/σ^2 is far less than unity over the range of gas velocities studied in the bubbling flow regime. That the fluctuation dynamics of the studied fluidizing system is deterministic is further confirmed. However, different tendency of deterministic level of system dynamics was found for different gas velocities and different location distance from the distributor. At low gas velocities, intermittent gas bubbles led to intermittent pressure fluctuations; therefore, the more deterministic dynamics and the quite small ε/σ^2 were observed. But the pressure waves would be attenuated at the process of propagation up to the surface of the bed and the deterministic level of dynamics would be lowered. So at low gas velocities, ε/σ^2 at 0.40 m above the distributor was greater than that at 0.09 m above the distributor. With gas velocity increases, gas bubbles become gradually irregular and the deterministic level of the system dynamics was reduced as ε/σ^2 increases. But there is a maximum for measurements at distance of 0.4 m above the distributor. This was because the bed expanded gradually with increasing gas velocity; the mean bed height reached 0.65 m when gas velocity reached 0.335m/s corresponding to the maximum of ε/σ^2. At this time, the location of pressure measurement at 0.4 m above the distributor, it became the main body of the bed and attenuation of pressure waves began to decline. Thus the deterministic level of the system dynamics begins to gradually increase at much higher gas velocities.

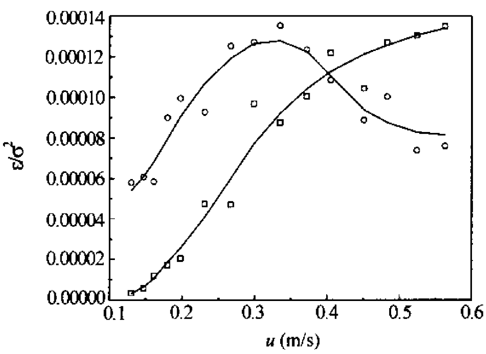

Fig.4 The mean prediction error ε/σ^2 at different gas velocities

□ distance from distributor 0.09m; ○ distance from distributor 0.40m

CONCLUSIONS

A new method for detecting the deterministic dynamics underlying pressure signals is proposed to study the nature of pressure fluctuations generated by deterministic or stochastic process. Data analysis using prediction error confirmed that the fluctuation dynamics of fluidizing system is deterministic. The different deterministic levels of dynamics at different locations of pressure measurements and at different gas velocities were analyzed.

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