DYNAMIC PROPERTIES OF TWO-COMPONENT PARTICLES IN DENSE GAS-SOLID FLUIDIZED BED

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ABSTRACT

Recurrence plots and recurrence quantification were used to analyze pressure fluctuation signals in a dense gas-solid fluidized bed. Parameters including determinism (QDET), average diagonal line length (Ql), and laminarity(QLAM) were determined from the recurrence plot. Comparative analysis of the flow images and parameters was performed. The bubbles become larger, and the chaotic characteristic in the fluidized bed strengthens with increasing gas velocity. The biomass particles are preferentially blown to the upper layer and mixed with quartz sand at high gas speed. Large bubbles in the fluidized bed can be easily broken by biomass particles with increasing biomass concentration. The presence and movement of large cylindrical biomass lead to decreased bubble size, uniform energy, and reduced QDET, Ql, and QLAM. The minimum fluidization velocity of the mixed flow of quartz sand and biomass is 0.5m/s. The pressure drop increases with increasing bed height and is not related to biomass concentration.

KEYWORDS
Recursive plots; recurrence quantification analysis; pressure fluctuation signals; cylindrical biomass

INTRODUCTION

Dense gas-solid fluidized bed has been widely used in chemical engineering and energy conversation [1]. In industrial engineering, most of biomass particles are larger and cylinder-shaped. The fluidization of cylindrical biomass and bed material is more complex [2, 3]. Studies on the fluid-dynamic behaviors of non-spherical particles have been performed worldwide, but the full knowledge on the complex flow properties are still lacking[4]. The study based on pressure fluctuation signals has attracted considerable attentions[5, 6], because the measurement of pressure signal is convenient and relatively cheap[7]. Pressure fluctuation signals are primarily caused by bubbles’ formation and coalescence, reflecting the movement of particles and the behavior of bubbles[8]. Si and Guo [9] investigated the fluidization behaviors of binary mixtures of biomass and quartz sand in bubbling fluidized bed. Hilbert-Huang transformation was used by analyzing the pressure fluctuation signals[10]. The dynamic characteristics of two-component have been researched from the aspect of time domain, frequency domain, and phase-space structure by nonlinear analysis method[11, 12]. However, many dynamic parameters assume that the time series is much longer. Recurrence plots (RP) is an effective analysis way for shorter time series and less computing time than other methods[13-14]. It was introduced first by Eckmann et al. [15] to observe the recurrences. Zbilut and Webber[16, 17] developed the recurrence quantification analysis (RQA) to extract quantitative information from recursive plots. Babaei et al.[18] investigated the hydrodynamics of gas-solid bubbling fluidization using RP[19]. In Llop’s paper[20], the pressure signals of gas-solid fluidization were analyzed by RP and RQA[21]. Recurrence rate (RR) was employed to research pressure fluctuation signals and the results were confirmed by FFT analysis [22].

In this paper, pressure signals were obtained from the experiment of cylindrical biomass and quartz sand, and the characteristic parameters were determined from recursive analysis. Our aim here is to understand the dynamic properties of two-component particles in fluidized bed and the mechanisms that cause agglomerating and bridging are further studied.

MATERIALS AND METHODS

Experimental system. The schematic of the experimental setup is shown in Fig. 1. The setup mainly contains four parts, namely, fluidized bed, gas system, measurement system, and image acquisition system. The fluidized bed is made of organic glass, and has a height of 1000mm. Pressure measuring points are arranged at different heights of the bed wall and wind chamber. Fluidizing air is supplied from root blower and adjusted by a rotameter. Pressure signals were measured by a pressure sensor, transferred to a data collector, and entered into the computer for analysis. The frequency for each measurement was set as 100Hz, and more than 1024
data were collected each time. The motion of the bed particles was recorded by a high-speed camera to observe the flow properties of biomass particles and quartz sand.

The weight percentage of biomass is designated as \( w \), and the height of particles (biomass and quartz sand) in the fluidized bed is \( H \). The percentage of biomass ranges from 0% to 20%. Biomass particles and quartz sand are shown in Fig. 2. Quartz sand exhibits a density of 2.65 g/cm\(^3\) and an average size of 0.8 mm. The cylindrical biomass particles feature a length of 10 mm, a diameter of 10 mm, and a small density of 0.6-0.9 g/cm\(^3\).

Methods. Recursive plots (RPs) is an important tool used to analyze nonlinear time series for identifying the internal structure and dynamic properties of 2D images. The reconstructed phase space is reflected in the 2D plane, and the black dots represent the recursive state of the system.

No two identical states exist in actual dynamic systems. Recurrence refers to the state of \( X_i \) to \( X_j \), and the distance is less than the predefined cut-off distance (\( \epsilon \)). The mathematical expression of m-dimensional phase space in RPs is:

\[
R_{ij}^m = \Theta(\epsilon - \|X_i - X_j\|), i, j = 1, 2, ..., N
\]

where \( \Theta(\bullet) \) is the Heaviside function expressed as follows:

\[
\Theta(x) = \begin{cases} 
1, & x \geq 0 \\
0, & x < 0 
\end{cases}
\]

RPs can be classified based on texture features into four categories. Fig. 3a presents a uniform structure from random signals; the structure consists of a diagonal line and a small number of isolated points. Fig. 3b shows a periodic structure obtained by sinusoidal signals; the structure exhibits a clear trend of the main diagonal line. The texture is grid shape because sinusoidal signals are strictly periodic. Fig. 3c shows that the drift structure extends from the center of the main diagonal line and is mainly caused by the slow variation in the parameters of the system. Fig. 3d indicates a mutation structure in, which has large black and white area and is due to the sudden change of the system.

**FIGURE 1**
Schematic diagram of the experimental device
1-Roots blower 2-control valve 3-bypass valve 4-rotameter 5-air distributor plate 6-bubbling bed 7-switch 8-pressure sensor 9-USB data collector 10-computer 11-router 12-high-speed camera

**FIGURE 2**
Bed particles in experiment: (a) cylindrical biomass; (b) quartz sand.
Recurrence quantitative analysis (RQA) is a method used to quantify recurrence based on the distribution of basic graph dots and segments. The major RQA factors used in this experiment are defined as follows:

Determinism ($Q_{DET}$): the percentage of recurrence points along the diagonal line

$$Q_{DET} = \frac{\sum_{l} l \cdot p(l)}{\sum_{l} p(l)}$$

where, $P(l)$ is the probability of the length $l$ of the diagonal lines, and $l_{min}$ is the minimum length of the analytical diagonal, and is generally 2.

Average diagonal line length ($Q_L$): the average period of the system is represented by the average length of the diagonal line

$$Q_L = \frac{\sum_{l} l \cdot p(l)}{\sum_{l} p(l)}$$

Laminarity ($Q_{LAM}$): the percentage of recurrence points in the vertical line

$$Q_{LAM} = \frac{\sum_{v} v \cdot P(v)}{\sum_{v} P(v)}$$

where, $P(v)$ is the probability of the length $v$ of the vertical lines, and $v_{min}$ is the minimal length of the vertical line, and is generally 2.

RESULTS AND DISCUSSION

Analysis of flow images. The flow images of the fluidized bed are collected by a high-speed camera (Fig. 4). The initial bed height is 60mm, and the bed particles start to flow at 1m/s. The bed contains few small bubbles. At this flow speed, the maximum flow height is 100mm and the cylindrical biomass particles are mainly located in the upper part of the quartz sand. When the gas velocity is 1.5m/s, the height of the fluidized particles increases to 120mm, and the bed contains many large bubbles. At the superficial air speed of 2.0m/s, the material particles reach the height of 160mm and mixing in the bed is intensified. Large biomass particles fall back to the
middle or bottom of the fluidized bed, thereby increasing the number of small bubbles.

In summary, the fluidized bed contains big bubbles at high gas velocity. As the gas speed is small, biomass particles are mainly distributed in the upper part of the quartz sand. Particle mixing is intensified with increasing gas speed. The biomass particles easily fall down and are quickly brought into the upper space in the fluidized bed. As the biomass concentration increases (Fig. 5), large bubbles in the bed can be easily broken by the biomass particles; moreover, small bubbles are found around the biomass particles. On the one hand, large biomass particles block the fall of the quartz sand. On the other hand, the rising speed of the biomass particles is faster than that of the surrounding quartz sand. The upper layer of the quartz sand receives extrusion and moves down around the biomass, leading to the formation of small bubbles.

**Pressure drop and gas velocity.** A certain relationship exists between gas velocity and pressure drop (ΔP) and is always used to determine the minimum fluidization velocity (v_{mf}). First, the pressure drop increases linearly with gas velocity and then fails to rise; the highest point is called the static pressure. The fluidized bed is transformed from the stationary state to the fluidized state, and the corresponding gas speed is the minimum fluidization velocity. Fig. 6 shows the relationship between pressure drop and gas velocity at different bed heights and biomass concentrations, as measured by depressurization. The biomass and initial bed height minimally affect the minimum fluidization velocity, which is set as 0.5 m/s in this experiment. When the gas speed is 0.25-0.5 m/s, the pressure drop increases gradually and is then stabilized. During the process, fluidization of the bed particles is difficult and the biomass is mainly distributed among the layer of quartz sand. The bubbles pass through the bed material and this state belongs to the fixed bed. As the gas velocity continues to increase, the particles start to flow and the pressure drop is maintained within a stable range. The mixing degree of biomass and quartz sand increases, and the bubbles change dramatically. The diagram also indicates that the pressure drop increases with increasing bed height. The pressure drop values are 1400 Pa at the bed height of 40 mm and 1800 Pa at the bed height of 60 mm.

As shown in Fig. 7, the mass fraction of biomass minimally affects the pressure drop. When the gas velocity is higher than 2.3 m/s, the flow state changes from the bubbling bed to the turbulent bed, and the pressure drop slightly decreases by about 150 Pa. The pressure fluctuation in the fluidized bed is influenced by particles and bubbles. At a high biomass concentration (w=20%), the biomass particles play an important role in increasing the weight of the bed material and the gas-solid drag force. Thus, the pressure drop is slightly larger than the flow of quartz sand. At a low proportion of biomass (w=5%), the formation and aggregation of the bubbles play an important role and do not considerably change. In general, the effect of the addition of biomass on the pressure fluctuation is limited, unless the added amount is large.

**Recurrence plots.** Fig. 8 shows that the recurrence plots of quartz sand flow alone are mainly composed of diagonal lines and recursive points, indicating strong periodicity and recursion. The number of diagonal lines increases as the gas velocity increases from 0.4 m/s to 0.6 m/s. The flow pattern is converted from the fixed state into the fluidized state. The small bubbles generated in the process, penetrate the bed material and reduce the vibration of the material particles in the fixed state, thereby increasing the periodicity and determinism. As the gas velocity continues to increase, the bubble becomes larger, the turbulence is enhanced, and the determination of the system is reduced. Thus, the determination increases at first and then declines sharply. At 2.0 m/s, the fluidized bed changes from bubbling into turbulent one. The recursive graph in Fig. 8d shows many horizontal and vertical lines, indicating that the system experiences abrupt mutation caused by drastic change in large bubbles.

![Flow regimes of cylindrical biomass and quartz sand at 2.0 m/s:](image)

**FIGURE 5**

Flow regimes of cylindrical biomass and quartz sand at 2.0 m/s: (a) w=5%; (b) w=10%; (c) w=20%.
FIGURE 6
Pressure drop with bed height and gas velocity under different biomass concentration:
(a) $\omega=0\%$; (b) $\omega=5\%$; (c) $\omega=10\%$; (d) $\omega=20\%$.

FIGURE 7
The relationship between pressure drop and biomass concentration: (a) $h=50\text{mm}$; (b) $h=60\text{mm}$.

FIGURE 8
Recurrence plots of quartz sand at different gas velocities:
(a) $v=0.4\text{m/s}$; (b) $v=0.6\text{m/s}$; (c) $v=1.0\text{m/s}$; (d) $v=2.0\text{m/s}$.
When the mass fraction of biomass increases, the recursive graphs in Figs.9 and 10 demonstrate few recursive points compared with that of one component of quartz sand but show many diagonal lines. This finding indicates that the biomass weakens the recursive system but maintains strong chaos characteristic because bubbles become larger with increasing mixing height, thereby ostracizing the surrounding particles. The biomass particles differ from quartz sand in terms of shape, volume, and density. The rising biomass particles will fall back into bubbles and split them into smaller ones. The pressure fluctuations in the bed will tend to be gentle. By contrast, a block structure is evident at \( v = 2.0\, \text{m/s} \) mainly because increasing the gas velocity will increase the size of the bubbles.

**Recurrence quantification analysis.** Fig.11 shows the variation in \( Q_{\text{DET}} \) in the fluidized bed. Under the fixed bed condition (\( v = 0.4\, \text{m/s} \)), the gas passes through the gap between the bed material and cannot be converted into bubbles; as such, the bed material is in slight vibration state, inducing the pressure fluctuation signal to be close to that of the random state. As the flow state changes into bubble flow (\( 0.4\, \text{m/s} < v < 0.7\, \text{m/s} \)), bubbles are gradually generated in the bed. The size of the bubble increases with increasing gas velocity, thereby increasing the \( Q_{\text{DET}} \) in the system. Moreover, the aggravated turbulence will reduce the \( Q_{\text{DET}} \). As a result, the determination of the system increases sharply at first and decreases later. When the gas velocity continues to increase, the flow of the bed is completely developed into bubble flow, and \( Q_{\text{DET}} \) minimally changes in the bubbling phase with increasing gas velocity. When the biomass concentration increases, the \( Q_{\text{DET}} \) decreases gradually; hence, the presence of biomass can reduce the \( Q_{\text{DET}} \) of the system.

Fig.12 shows the changes in \( Q_{\text{LAM}} \) with gas speed, indicating the characteristics of the intermittent system. The \( Q_{\text{LAM}} \) of the system decreases first and then increases with increasing gas velocity. In the fixed bed, \( Q_{\text{LAM}} \) with different biomass concentrations is very close to one another and decreases with increasing gas speed. When the bed is in the bubble flow state, \( Q_{\text{LAM}} \) increases with increasing gas velocity and the added biomass particles decrease the \( Q_{\text{LAM}} \); this finding is consistent with the results of recursive graph analysis. At gas speed higher than 0.7 m/s and biomass concentration of 5%, \( Q_{\text{LAM}} \) is similar to that of one component of quartz sand. At the mass fraction of 10%, \( Q_{\text{LAM}} \) is relatively low, indicating that the biomass is favorable to the uniform distribution of bubbles, thereby increasing the continuity of the system.

**FIGURE 9**
Recurrence plots at 0.4m/s: (a)\( w = 5\% \); (b)\( w = 10\% \).

**FIGURE 10**
Recurrence plots at 2.0m/s: (a)\( w = 5\% \); (b)\( w = 10\% \).
FIGURE 11
The variation of $Q_{\text{DET}}$ with gas velocity at different biomass concentration.

FIGURE 12
The variation of $Q_{\text{LAM}}$ with gas velocity at different biomass concentration.

FIGURE 13
The variation of $Q_{\text{i}}$ with gas velocity at different biomass concentration.
Fig. 13 shows $Q_s$ with increasing gas velocity and represents the average period of the system, similar to the curve of $Q_{Det}$. At gas speed lower than 0.7 m/s, the periodicity of the system is influenced by bubbles size and gas turbulence. The performance increases first and then decreases. At high gas speed, the flow of quartz sand exhibits a trend to turbulent fluidization and the bubbles and particles are mixed violent; as such, the $Q_s$ begins to decline. The addition of biomass evidently affects the bubbles. The average period of the system decreases with increasing biomass content. The influence of gas velocity on the average period also decreases because the presence of biomass can accelerate the breakup of bubbles, resulting in reduced size and even distribution of the bubbles.

**CONCLUSIONS**

The minimum fluidization velocity of the mixed flow of quartz sand and biomass is 0.5 m/s. The pressure drop increases with increasing bed height and is not related to biomass concentration. Based on analysis of particles motion at different times, the fluidized bed contains large bubbles at high gas velocity. The biomass particles are preferentially blown to the upper layer and mixed with quartz sand at high gas speed. Large bubbles in the fluidized bed can be easily broken by biomass particles with increasing biomass concentration. The increase in the gas velocity enhances the chaotic characteristics of the flow in the bubbling bed. The existence of large biomass particles will disrupt the movement of bubbles, resulting in large bubbles generating small bubbles; as such, the dissipation energy is intensified. Furthermore, the system tends to be stable and $Q_{Det}$, $Q_s$, and $Q_{Lam}$ decrease with increasing biomass.

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