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Multi-scale nonlinear analysis of drying dynamics in the mixed pulsed drying fluidized beds

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ABSTRACT

Abundant information resides in the pressure signal of a fluidized bed, especially when the pressure signal of that bed is mixed with steady flow, and the pulsed flow is more prevalent. In this paper, the authors established a stable and pulsed flow fluidized bed experiment platform. They also collected pressure signals with different times, different frequencies and different gas flow rates in the drying process. The pressure signals were analyzed by two approaches. One is based on the use of the multi-scale complexity entropy causality plane, and the other relies on a recurrence plot. With the drying characteristics of wet particles in the bed and flow pattern, the focus was on influence factors such as time lapse, air intake ratio and pulse frequency on both drying efficiency and the characteristics of complex nonlinear dynamics were analyzed. A study of the micro and macro mechanism of flow characteristics is also presented. The results show that the two approaches (i.e., methods) have a higher accuracy in judging the change of the interaction force between moist particles and the change of flow characteristics. The drying efficiency can be deduced by analysis of the dynamic characteristics of the fluidized bed; thus, the multi-scale complexity entropy causality plane and the structure of the recurrence plot corresponding to the best drying efficiency are obtained. A recommended reference range of the three parameters of a recurrence plot that are good for drying will be presented, which corresponds to the ratio of the stable flow and the pulsed flow.

1. Introduction

A fluidized bed plays an important role in industrial applications, and it is an important aspect of fluidization technology. In industrial production, the efficient and stable operation of a fluidized bed has a very important economic value and safety significance. The pressure fluctuation signal in a gas-solid fluidized bed contains valuable information [1], which reflects the running state and the flow pattern transformation of the fluidized bed. Moreover, the bubble size, particle properties and geometry of the fluidized bed have an important influence on the flow characteristics. The distribution and size of bubbles affects the flow structure and motion law of the gas-solid two-phase flow. The aggregation and splitting behavior of bubbles play a decisive role in the transfer characteristics of particle mixing, heat transfer, and mass transfer. Through the pressure fluctuation signal, we can get information about bubble behavior, particle movement and flow regime transformation [2]. Therefore, it is important to study the intrinsic nature of the pressure fluctuation signal to further investigate the dynamic characteristics of the gas-solid fluidized bed.

It is difficult to study the gas-solid two-phase flow due to its complex nonlinear dynamics. After years of research and development, three primary analytical methods have emerged, i.e., the time domain method, frequency domain method, and the time-frequency domain method [3–6]. Some results have been obtained in the analysis of the dynamic characteristics of the gas-solid two-phase flow. With the development of mathematical theory, multi-scale and nonlinear analysis have gained significant prominence. Many scholars have carried out nonlinear research on complex multi-phase flow theory from a multi-scale point of view. From microscopic and macroscopic perspectives, research on multi-scale resolution (frequency domain) [7] and multi-scale entropy (time domain) [8] enriched the studies leading to the evolution mechanism of flow patterns in a gas-solid two-phase flow. Xu et al. [9] used multi-scale entropy to analyze the pressure fluctuation signals in a fluidized bed; they also analyzed the signals of four typical flow patterns in a gas-solid fluidized bed and found that the characteristics of flow patterns in the fluidized bed would change at different gas flow rates. Thus, the multi-scale entropy of the pressure fluctuation can increase or decrease. The two-phase flow pattern in the fluidized bed was accurately identified by this method.

The multi-scale complexity entropy causality plane (MS-CECP) is a new nonlinear analysis method. Entropy is an important characterization of the complexity of nonlinear systems, which helps explain the dynamic behavior of the two-phase flow [10,11] Dou et al. [12] extend the complexity entropy causality plane (CECP) to propose a multi-scale complexity entropy causality plane (MS-CECP) and further use the

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proposed method to discriminate the deterministic characteristics of two-phase flow. Zhuang et al. [13] proposed a multi-scale weighted complexity entropy causal plane (MS-WCECP), which introduced permutation entropy into weighted entropy and performed much better in anti-noise ability as well as distinguishing different signals. They used MS-WCECP to study the nonlinear characteristics of oil-gas-water three-phase flow structure, and the results show that MS-WCECP can effectively describe the transformation of three-phase flow structure. The advantage of this method has been verified in the oil-water and gas-liquid two-phase flow. However, it has not been applied to the gas-solid two-phase flow field. Yang et al. [14] [studied the flow characteristics of oil-water mixtures in a vertical pipe by using MS-CECP. They found that multi-scale entropy analysis can effectively evaluate instability in two-phase flows. Fan et al. [15] analyzed the conductance fluctuating signals of three typical gas-liquid flow patterns. They used MS-CECP to analyze flow structure stability and micro dynamic behavior of typical flow patterns, thereby proving the feasibility of the MS-CECP in flow pattern identification and dynamics specificity analysis.

In gas-solid two-phase flow analysis, the recurrence plot is more practical in identifying flow patterns and analyzing dynamic characteristics. The recurrence plot was proposed by Eckmann et al. [16]. It is an analytical method used to observe the internal dynamic characteristics of nonlinear time series from two-dimensional graphs. The recurrence plot is also an effective tool for judging the regularity of data. Behzad et al. [17] and Miquel et al. [18] analyzed the characteristics of the pattern, and found that macro phenomena such as bubble eruption, bubble generation and bubble coalescence can be reflected by the distribution of the recurrence plot structure. To quantify recursive analysis, Zbilut et al. [19] and Trulla et al. [20] quantitatively analyzed the gas-solid two-phase flow by using the eigenvalues of a recurrence plot, including a recursive rate (RR) and deterministic structuring (DET) of systems in higher dimensional space [20]. Their analysis enabled them to obtain the characteristic ranges corresponding to different flow patterns. Hossein et al. [21] and Maryam et al. [22] analyzed the characteristics of dynamics in fluidized beds under different conditions and found that the variance of the RR could reveal the peak dominant frequencies of different dynamic systems, and the Shannon entropy has more consistency with fluidized bed hydrodynamics. Average diagonal lengths, trapping time and entropy as well as other eigenvalue trends were analyzed by Wang et al. [23] and Zhou et al. [24]. They found that different flow regimes have different eigenvalue trends. Thus, a new technique for prediction of transition velocity from bubbling to turbulent fluidization regime was proposed.

In the mixed pulsed gas flow of drying fluidized beds, the gas flow contains two streams: one is continuous flow and the other is pulsed flow [28]. The pulse gas flow rate oscillates periodically with time, which can enhance the gas-solid contact and improve the fluidization quality especially for biomass which belongs to Geldart's Group D particles with high moisture content, low bulk density and irregular shape properties. Several pulsed flow fluidization studies have found significant improvements in bed performance when comparing the single pulsed and continuous flow fluidization. Zhang et al. [26] investigated the drying kinetics of activated alumina to assess the advantages of a pulsed fluidized bed; he found the drying rate is higher to some extent in a pulsed fluidized bed than that in a fluidized bed during a constant drying period even at low average superficial air velocity. Jia et al. [25] studied the drying of biomass materials in a pulsated fluidized bed. By observing the flow pattern of air bubbles and after analyzing the drying rate, they found that the gas-solid contact effect is best when the frequency is <3 Hz. Bizhaem and Tabrizi [27] also found that increasing the pulsation frequency can decrease the bed expansion ratio, bubble diameter, and velocity in a pulsed fluidized bed.

Most research on the dynamics of gas-solid two-phase flows focus on the qualitative analysis of the granular dynamics mechanism of gas-solid two-phase flows. However, little research has been done on the drying dynamics characteristics of gas-solid two-phase flow, especially for the quantitative analysis of the drying dynamics of mixed pulsed gas-solid two-phase flow. Pressure signals in a mixed pulsed fluidized bed are usually analyzed by the multi-scale complexity entropy causality plane and recurrence plots [16–22]. This research analyzes the effect of gas flow ratio and pulse frequency on flow structure and drying rate. Research deliverables include a quantitative analysis of drying dynamics characteristics of a mixed pulsed fluidized bed and a nonlinear analysis model to determine the drying efficiency.

2. Experimental setup

This experiment focuses on the pulsed fluidized bed and collects relevant pressure data. Fig.1 provides a schematic of the experimental setup. The main body of the experimental section is made of Plexiglas. Air is driven by the roots blower and preheated by an air preheater. The pulsed air flow branch is controlled by an electromagnetic valve to capture the intermittent entry of airflow. The gas is heated in a preheater before entering the fluidized bed, and the temperature of the intake gas is collected by a temperature collector in the intake pipe before entering the fluidized bed. An air distributor is arranged at the bottom of the fluidized bed, and the opening rate is 22.67% [28]. The pressure signals are collected in the main fluidized bed. The positions of pressure measurement points in the experiment are: underneath the air distributor, at the top of the air distributor, on the bottom of the material, in the middle and upper part of the material. The measuring point at the bottom of the material is mainly used to monitor the influence of bubbles on the pressure signal, while the upper and middle measuring points are used to monitor the development and merger of the bubbles. The partial pressure signals collected under different working

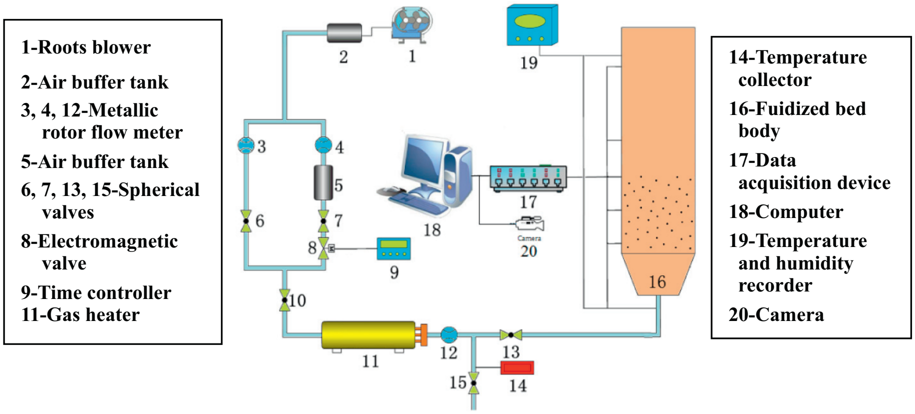

Fig. 1. Schematic diagram of the experiment system.