Powder Technology xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Powder Technology

journal homepage: www.elsevier.com/locate/powtec

Monitoring of liquid sprayed conical spouted beds by recurrence plots

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ARTICLE INFO

Article history:
Received 27 April 2016
Received in revised form 15 December 2016
Accepted 26 December 2016
Available online xxxx

Keywords:
Conical spouted bed
Pressure fluctuation
Acoustic emission
Recurrence plot
Hydrodynamic monitoring

ABSTRACT

In this study, the chaotic behavior of gas-solid flow in a laboratory scale conical spouted bed during spraying of water on the sugar particles was investigated using non-linear analyses of pressure fluctuations (PFs) and acoustic emission (AE) signals. The phase space trajectories, recurrence plots (RP) and recurrence quantification analyses (RQA), as powerful non-linear techniques, were used for monitoring of the bed hydrodynamics. It was concluded that the reconstructed phase space trajectories of both PFs and AE signals approach to a slim and elongated patterns with the formation of agglomerates due to injection of water into the bed. Examinations of the RP maps show that the contribution of patches with larger distances increases by an increase of water content in the bed. Moreover, the RQA results show that the maximum length of diagonal lines of RPs increases by injection of the water into the bed showing that the hydrodynamic status of the bed becomes more deterministic. The results of this work show the high potential of these methods for proper understanding of the hydrodynamics of spouted beds with liquid injection and associated agglomeration phenomenon.

1. Introduction

Conical spouted beds are gas-solid contactors successfully employed in numerous industrial processes such as gasification, combustion, granulation, coating and drying of suspensions, solutions, and pastry materials [1–3]. These beds show good particle mixing and liquids can be easily sprayed into the bed through a nozzle placed at top or bottom [1]. Coating and granulation processes usually involve the presence of a liquid in the bed. The addition of liquid leads to an increase in particle cohesiveness and promotes de-spouting and bed malfunctioning in some cases. Therefore, the hydrodynamics of a spouted bed may change over time due to instabilities, such as intense oscillation in fountain height, vigorous swings of the spout from side to side, choking and consequent slugging of the spout imposed by particle size changes and cohesiveness. Since the performance of liquid sprayed conical spouted beds strongly depends on their hydrodynamics status, their monitoring is crucial to control the product quality [4].

There are many measurement techniques to determine the hydrodynamic properties of spouted beds, such as pressure fluctuations (PFs) [5–7], fiber optic (FO) [8,9], radioactive particle tracking (RPT) [10], capacitance tomography (CT) [11,12], computer-based video imaging [13,14] and acoustic emission (AE) signals [15]. Since pressure fluctuations are easily measurable and include effects of different dynamic phenomena taking place in the bed, such as individual and bulk movement of particles and formation and movement of agglomerates [16], many researchers have used pressure fluctuations for characterization of the system [5–7,16]. Since it is necessary to insert the pressure probe into the bed through an orifice, this measurement technique has some limitations at severe, corrosive and high pressure/temperature conditions. Furthermore, some other measurement problems might appear, such as blockage of the probe by solids [17]. Consequently, the need for developing other non-invasive monitoring techniques is clear. Recently, acoustic emission measurement technique has gained attention as it is a non-invasive, low cost, reliable measurement technique and applicable to a wide range of process conditions [18]. This technique has a potential to improve process understanding and to provide a basis for on-line monitoring and control of various processes. However, there are only two studies in the open literature on monitoring of AE signals in spouted beds [15,19]. Therefore, investigating the adoption of AE signals for monitoring the hydrodynamic status of spouted beds and its comparison with other known techniques, such as PF measurements, seems to be necessary.

Standard methods in time series analysis include statistical (e.g., standard deviation, skewness and kurtosis) or spectral analysis (e.g., fast Fourier transform, power spectrum). A proper understanding of the state of complex systems cannot be determined by linear methods in time and frequency domains. Various nonlinear analysis techniques, such as short-term predictability and attractor comparison, have been used for analyzing the dynamics of complex systems [20]. These

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http://dx.doi.org/10.1016/j.powtec.2016.12.075

Please cite this article as: C. Savari, et al., Monitoring of liquid sprayed conical spouted beds by recurrence plots, Powder Technol. (2016), http://dx.doi.org/10.1016/j.powtec.2016.12.075

nonlinear techniques are based on reconstruction of an attractor of dynamic evaluation of the system and allow extracting useful information about its dynamical state. However, these methods have some limitations, such as long term data sampling requirement, time consuming numerical calculations and uncertainty in the determination of embedding parameters [20,21].

In this study, a monitoring technique based on the recently introduced nonlinear analysis method of recurrence plot (RP) and recurrence quantification analysis (RQA) [22] of PFs and AE signals is developed for the detection of changes in hydrodynamics of a liquid sprayed conical spouted bed. The main advantageous feature of the RP is that a high-dimensional dynamical system, whose state space trajectory is difficult to visualize, can be represented in a two-dimensional plot. Another considerable characteristic of the RP analysis is that it provides useful information using a non-stationary and short-term data. In other words, difficulties associated with typical nonlinear analysis methods, such as long-term data samplings and time consuming algorithms, can be avoided when using the RP method. Although nonlinear analysis by RP has been used in the characterization of fluidized bed hydrodynamics [23–25], oil-water two phase flow [26,27], gas-liquid two phase flow [28], bubble and rimming flows [29,30], application of this method to spouted beds is rare [31]. Therefore, in this study, in order to determine the hydrodynamic state, two kinds of recurrence plots (thresholded RP and unthresholded RP) and an RQA parameter (maximal length of diagonal line) of both pressure fluctuations and acoustic emission signals were obtained from a conical spouted bed and analyzed.

2. Experimental method

The experimental data were obtained in a full circular conical spouted bed of diameter 150 mm with a conical base of internal angle 45° and an inlet orifice diameter of 6 mm. A schematic diagram of the bed with bottom liquid spray is shown in Fig. 1. The spouting gas flow rate was supplied from a screw type air compressor operating with a supply pressure of 8 bar at a maximum flow rate of 0.05 m^3/s. A pressure regulator and an air tank of 30 L in volume were placed between the supply line and the spouted bed gas inlet to eliminate air flow rate fluctuations. Tap water was sprayed into the bed with a nozzle positioned at the center of the air inlet orifice.

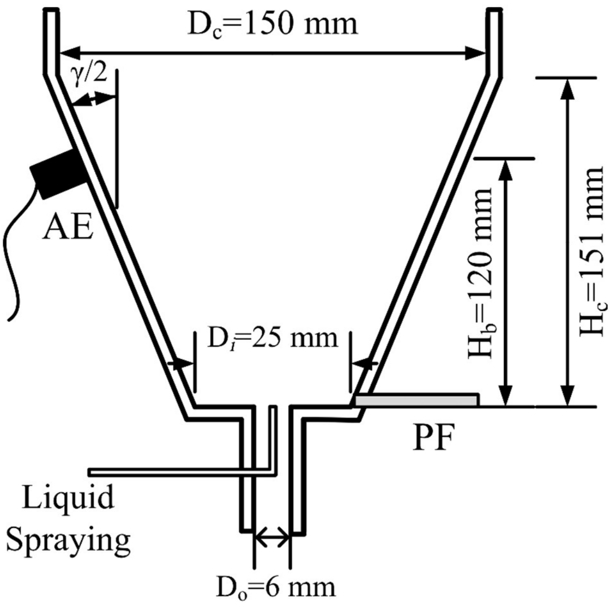

Fig. 1. Schematic of conical spouted bed.

High speed camera photography was employed in a half column conical spouted bed for visualizing the flow patterns during water injection and drying periods. The half bed was simply sliced full column with a flat Plexiglas sheet attached to the front open surface for visual observation and photography. Both full and half beds had the same geometrical dimensions. Images were acquired with a camera (UI-2210SE, IDS Co.) equipped with a 16 mm PENTAX lens having a resolution of 640 × 480 pixels with the frame rate up to 200 frame/s (fps).

Differential pressure transducer (PX163-120D5V, OMEGA Engineering) connected to a 16 bit data acquisition board (National Instruments, USB-6351) was used to record PFs time series. The measuring port of the pressure transducer was connected to the base of conical section of the bed, as shown in Fig. 1, while the other port of the pressure transducer was left open to the atmosphere. The PFs time series were recorded at a sampling frequency of 500 Hz. The AE signals were measured by an omnidirectional back electret condenser microphone (Panasonic, WM-61 A) which had a frequency response of 0.02-20 kHz (sensitivity: -35 ± 4 dB, signal to noise ratio: >62 dB). The outlet signal from the microphone was recorded by a USB interface sound analyzer (ARTIMAN Instruments, ART-SA16) with a sampling frequency of 44 kHz. The AE sensor was installed by silicon grease externally to the outer surface of the bed at 120 mm above the base of the conical section. Location of the acoustic sensor was selected based on the findings of Oliveira et al. [15] who showed the similarity of AE signals measured at different positions.

PFs and AE signals were recorded continuously during the spraying of water on the sugar particles having 720 μm mean diameter and density of 1580 kg/m^3. In the experiments, water was sprayed every 2 min into the bed with a flow rate of 3 mL/min for 10 s until the bed collapsed. In order to compare the signals during water injection with the ones measured in the dry bed, the PFs and AE signal measurements were started 2 min prior to the first water injection interval. The static bed height and ratio of the inlet gas velocity to minimum spouting gas velocity (U/U_{ms}) were maintained constant at 120 mm and 1.2, respectively. To eliminate possible effects of the initial packing status on the measurements, the bed was spouted for 10 min prior to spraying of water in each experiment. Visual observation of the bed hydrodynamics was performed in order to characterize the bed behavior during experiments.

3. Theory

3.1. Recurrence plots

Recurrence plot visualizes recurrences in the dynamics of a dynamical system [22]. In literature there are several variations of recurrence plots. Thresholded recurrence plot (TRP), is a widely used kind of recurrence plot that represents repeated states of a phase space of the system. The TRP is a two-dimensional squared matrix, R, which is mathematically expressed as [32]:

$$R_{i,j} = \Theta\left(\varepsilon - \left\|\vec{x}_i - \vec{x}_j\right\|\right)\ i,j = 1,2,3,\dots,N \quad (1)$$

where N is the number of state space points, $\vec{x}_i, \vec{x}_j \in R^m$ are i-th and j-th points of the m-dimensional state space trajectory, ε is a threshold distance, ‖.‖ is the norm and Θ is the Heaviside function. In fact, the matrix R compares the states of a system at times i and j. If the states are similar (the norm is less than ε), this would be marked by a 1 in the matrix, i.e., $R_{i,j} = 1$, and a black spot would appear on the plot at coordinate (i,j). If, on the other hand, $\vec{x}_i$ and $\vec{x}_j$ are rather different (the norm is greater than ε), the corresponding entry in the matrix would be $R_{i,j} = 0$ and a white spot would appear on the plot. In other words, this matrix can tell when similar states of the underlying system have occurred.

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