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Investigating the hydrodynamics of high temperature fluidized bed by recurrence plot

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ABSTRACT

Effect of temperature on the hydrodynamics of bubbling gas–solid fluidized beds was investigated using recurrence plot (RP) and recurrence quantification analysis (RQA) due to their capabilities for determining the whole bed complexity in a simple way. For this purpose, pressure fluctuations of a fluidized bed of sand particle were measured at various gas velocities and temperatures. Recurrence quantification analysis showed that by increasing the temperature up to 300 °C, both determinism and laminarity increase due to formation of larger bubbles whereas entropy and recurrence rate decrease. To better detecting the different structures of in the bed recurrence plot at higher temperature, pressure fluctuations were also decomposed through wavelet transform. It was shown that at low gas velocity, the macro structures became dominate with increasing the bed temperature due to increase in the rate of bubble coalescence. The bubble diameter was estimated from the incoherent component of the cross power spectra of pressure signals at various temperatures and velocities. The incoherent results and standard deviation of measured pressure fluctuations confirmed that by increasing the bed temperature up to 300 °C, bubbles grow up to a maximum diameter, after which they became smaller. In addition, the trend of the largest positive Lyapunov exponent was estimated through the recurrence plot patterns. It was shown that a bubbling fluidized bed is a chaotic system at higher temperatures. It was found a maximum in the estimated largest positive Lyapunov exponent at 300 °C corresponds to the larger bubbles.

1. Introduction

Many industrial fluidized beds, which are used in many processes such as combustion, gasification and fluid catalytic cracking, operate at high temperature [1–3]. Investigation of the hydrodynamics of fluidized beds through measurement of bed pressure is easy to perform. Some remarkable advantages of pressure signals are that they are easy to measure, have high accuracy, and are relatively inexpensive to obtain, do not alter the local hydrodynamic considerably and include the effect of many dynamic phenomena taking place in fluidized beds [4]. However, most of such measurements have been carried out at ambient temperatures.

Fan et al. [5] explored the major sources of pressure fluctuations in a fluidized bed. They indicated that the origin of pressure fluctuations lies in phenomena such as coalescence, motion and formation of bubbles as well as jet flow of the gas. Hartman and Trnka [6] analyzed pressure fluctuations in the frequency domain by fast Fourier transform. They showed that this method is able to recognize alterations in the hydrodynamic state of the bed caused by minor changes in the bed mass and size of particles. Using the wavelet transform, Guo et al. [7] decomposed pressure signals into approximation and details at different resolutions and showed that the number of peaks in the sixth detail signal represents the number of bubbles passing through the pressure probe measurement region over the sampling time. In the recent years, new analytical techniques of fuzzy c-means clustering [8] and least square support vector machine [9,10] also have been proposed to study the complex dynamics of gas-solid systems.

So far, a few experimental studies have been reported on hydrodynamics of fluidized beds at high temperatures. The majority of these investigations, however, were focused on the effect of temperature on minimum fluidization velocity and regime transition from bubbling to turbulent [11–14]. Correlations offered by Kunii and Levenspiel [2] and Formisani et al. [15] for predicting bubble size and minimum fluidization velocity predict an increase in the bubble size and a decrease in the minimum fluidization velocity by increasing the bed temperature. Hatate et al. [16] used Geldart B particles in their investigation and reported that the bubbles size increases by increasing the bed temperature from ambient to 327 °C. Sanaei et al. [17] reported that solids mixing and diffusivity of Geldart B particles increase by increasing temperature up to

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Nomenclature

d_0	initial distance between trajectories
d	distance between trajectories
d_{pi}	particle diameter (μm)
$\overline{d_p}$	mean particle diameter (μm)
D_b	bubble diameter (m)
DET	determinism
ENT	entropy
f	frequency (Hz)
j	wavelet decomposed information level
k	wavelet decomposed time lag coefficient
LAM	laminarity
L/D	aspect ratio
l	length of diagonal lines
v	length of vertical lines
l_{min}	length of diagonal lines minimum
v_{min}	length of vertical lines minimum
N	number of time series points
m_i	mass fraction of particles of size d_{pi}
$P_x(t)$	pressure time series (Pa)
$P(l)$	probability of the length l of the diagonal lines
$P(v)$	probability of the length v of vertical lines
$PSDF$	power spectral density function (Pa^2/Hz)
RP	recurrence plot
RQA	recurrence quantification analysis
RR	recurrence rate
$R_{i,j}$	recurrence plot matrix
t	time (s)
U_{mf}	minimum fluidization velocity (m/s)
U	superficial gas velocity (m/s)
x_i	time series
x_j	time series

Greek symbols

σ_{xy}	standard deviation of incoherent pressure time series
γ_{xy}	coherence
ε	radius threshold
Θ	heaviside function
λ	Lyapunov exponent
ρ_s	density of particles (kg/m^3)
Φ_{xy}	cross power spectral density of signals x and y (Pa^2/Hz)
Φ_{xx}	power spectral density of signal x (Pa^2/Hz)
ψ	mother wavelet function

300 °C and decrease at higher temperatures. They concluded that the bubbles size increases by increasing the bed temperature up to 300 °C and bubbles become smaller at higher temperatures. Nemati et al. [18] investigated the hydrodynamics of fluidized bed through analysis of pressure fluctuations in time and frequency domains. They used sand particles (Geldart B) in their experiments at various temperatures, ranging from ambient to 400 °C. They concluded that increasing the temperature up to 300 °C causes the bubbles to grow in size and reach their maximum size at 300 °C. Also, they showed that the drag force acting on the emulsion phase reaches a minimum at this temperature. Hagh-Shenas-Lari and Mostoufi [19] evaluated probabilities of fluidization regimes at various gas velocities and temperatures. They showed that the velocity of transition from bubbling to turbulent regime increases by increasing the bed temperature.

Hydrodynamics of fluidized bed is intrinsically non-linear. While only time and frequency domain analyses of dynamical variables of the fluidized bed at higher temperature are not capable of determining the whole complexity of the fluidized bed system, the study of nonlinear behavior of fluidization at higher temperature still is a relatively new subject. Therefore, non-linear methods of analysis have been utilized by many researchers for investigating this phenomenon [20]. All these methods are based on reconstruction of an attractor. However, they are associated with restrictions such as uncertainty in the reconstruction through experimental data. Parameters for the state space reconstruction were estimated by Zarghami et al. [21]. They stated that the value of these parameters may differ based on the technique applied for this purpose. In addition, when the dimension of the attractor is more than three, it cannot be visualized [22,23]. Conventional nonlinear analysis of a measured time series in a fluidized bed in the state space is not straightforward and still needs more research. In addition, Zarghami et al. [21] showed that there is a kind of uncertainty in reconstruction of attractor of fluidized bed from its pressure fluctuations. On the other hand, analysis of pressure fluctuations in the state space typically requires long term data sampling that leads to problems such as large capacity for data storage and long time required for data processing [24,25]. All these limitations have encouraged researchers to search for new techniques which can overcome these limitations.

Recurrence plot (RP) is a powerful tool that can solve some of the problems described above. This technique eliminates the necessity of long-term data sampling, does not need time series embedding, avoids time consuming algorithm and also enables analysis of non-stationary, short term and chaotic time series [26]. Moreover, using RP, any m-dimensional phase space trajectory can be represented visually in a two-dimensional space [26,27]. Furthermore, while embedding is required for reconstruction of an attractor in the state space, the RP may be constructed without embedding. In fact, all information contained in the embedded RP can be attained in the non-embedded one. Few researchers have used this technique to analyze pressure fluctuations of a fluidized bed. Wang et al. [28] used RP and recurrence quantification analysis (RQA) to analyze pressure fluctuations and recognize flow regimes through RQA parameters. Babaei et al. [27] employed the RP technique to analyze the hydrodynamics of gas-solid fluidized beds and were able to detect different hydrodynamic structures of the system (i.e., macro, meso and micro). Sedighikamal and Zarghami [29] used the RP and proposed a new technique for prediction of transition velocity from bubbling to turbulent fluidization regime. Babaei et al. [30] presented a new technique for on-line monitoring of fluidized bed hydrodynamics. They showed that determinism is sensitive to small changes in the particles size while is not sensitive to slight variations in the gas velocity. A combination of wavelet analysis and RQA methods was also used to characterize different structures in a fluidized bed [31,32].

In all above mentioned investigations, RP and RQA were applied to the data obtained at ambient temperature while industrial fluidized beds operate at high temperature. Hence, there is a need for investigating the hydrodynamics of fluidized beds at high temperature through RP and RQA. To address this issue, experiments were carried out in a fluidized bed up to 400 °C in the present work. While the RP is a qualitative representation of the hydrodynamic status of the fluidized bed, the RQA was introduced in this work to quantify the patterns in RPs of pressure fluctuations of fluidized bed. Recurrence rate (RR), determinism (DET), laminarity (LAM), entropy (ENT), Lyapunov exponent, as RQA parameters, were employed to investigate the nonlinearity of the complex dynamics of a fluidized bed at high temperatures in a simple