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Characterization of various structures in gas-solid fluidized beds by recurrence quantification analysis

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ABSTRACT

Gas-solid fluidized beds are widely considered as nonlinear and chaotic dynamic systems. Pressure fluctuations were measured in a fluidized bed of 0.15 m in diameter and were analyzed using multiple approaches: discrete Fourier transform (DFT), discrete wavelet transform (DWT), and nonlinear recurrence quantification analysis (RQA). Three different methods proposed that the complex dynamics of a fluidized bed system can be presented as macro, meso and micro structures. It was found from DFT and DWT that a minimum in wide band energy with an increase in the velocity corresponds to the transition between macro structures and finer structures of the fluidization system. Corresponding transition velocity occurs at gas velocities of 0.3, 0.5 and 0.6 m/s for sands with mean diameters of 150, 280 and 490 μm, respectively. DFT, DWT, and RQA could determine frequency range of 0–3.125 Hz for macro, 3.125–50 Hz for meso, and 50–200 Hz for micro structures. The RQA showed that the micro structures have the least periodicity and consequently their determinism and laminarity are the lowest. The results show that a combination of DFT, DWT, and RQA can be used as an effective approach to characterize multi-scale flow behavior in gas-solid fluidized beds.

1. Introduction

Gas-solid fluidized bed is one of the most complicated hydrodynamic processes. Typical particle-fluid two-phase flow patterns exhibit nonlinear and nonequilibrium dynamic characteristics with heterogeneous flow structure (Zhao & Yang, 2003). Due to the complexity of interactions between particles and fluid, hydrodynamics of fluidized systems has been intensively studied (Geldart, 1973; Chen & Fan, 1992; Jean, Eubanks, Jiang, & Fan, 1992; Zhao & Yang, 2003; Sasic, Leckner, & Johnsson, 2007; Zarghami, Mostoufi, & Sotudeh-Gharebagh, 2008; Tahmasebpour, Zarghami, Sotudeh-Gharebagh, & Mostoufi, 2013). Consequently, further studies are still required to understand fluidization phenomena and develop more accurate quantitative models to be used in design and optimization of fluidized-bed reactors.

Li and Kwauk (1994) demonstrated that the complex dynamics of a fluidized system may be reduced to three different structures in fluidized beds based on multi-scale approach: macro structures of high amplitude and low frequencies (up to 3 Hz) corresponding to large-scale phenomena such as large bubbles and bed surface oscillation, meso structures with frequencies in the range of 3–20 Hz referring to clusters and small bubbles, and micro structures of high frequencies of 20–200 Hz (Nyquist frequency) originating from impacts of solid particles, their motion and measured noise in the fluidized bed. Various analysis methods such as statistical (e.g., standard deviation, Skewness, Hurst exponent), spectral (e.g., Fourier transform, power spectrum, wavelet analysis) and CFD/DEM have been employed successfully to study the regimes and structures in fluidized systems. Zhao and Yang (2003) used Hurst analysis to analyze multi-fractal characteristics of pressure signals. Zarghami (2009) found that a shift of Skewness from negative to positive against velocity corresponds to shift from macro structures and finer structures of the flow. Wu, Kantzas, Bellehumeur, He, and Kryuchkov (2007) used wavelet energy calculated from detail coefficients of scale 1–6 decomposed from pressure fluctuations to investigate flow dynamics at micro- and meso-scales. Tsuji (2007) classified methods of numerical analysis (DEM) of gas-particle flows based on the concept of micro, meso and macro scale structures.

Hydrodynamics of fluidized bed are considered to be nonlinear (Daw & Halow, 1991; Glicksman, Hyre, & Farrell, 1994; Schouten & van den Bleek, 1998; Zarghami et al., 2008). The main idea of multi-scale structures is also nonlinearity. Consequently, a combination of the multi-scale method and the nonlinear analysis method is required to study the complexity of fluctuation dynamics in fluidized bed. In recent years, state space chaos analysis has been

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Nomenclature

a_j	approximation sub-signal
d	dimension of the system
d_p	particle size (μm)
D	bed diameter (cm)
D_j	detail sub-signal
DET	determinism
DFT	discrete Fourier transform
DWT	discrete wavelet transform
E_j^a	energy of approximation coefficient (kPa^2/Hz)
E_j^D	energy of detail coefficient (kPa^2/Hz)
E_x	energy of the PSDF (kPa^2/Hz)
f	frequency (Hz)
f_s	sampling frequency (Hz)
H	static bed height (cm)
i	counter
j	imaginary unit of the complex number
j	wavelet decomposed information level
k	time lag coefficient
l	length of a diagonal line
ν	length of a vertical line
l_{min}	predefined minimal length of diagonal lines
ν_{min}	predefined minimal length of vertical lines
L	number of the time-series segments
N	length of the time series
N_L	length of segments
P_4	probe position
$P(l)$	number of diagonal lines with length of l
$P(\nu)$	number of vertical lines with length of ν
$P_{xx}^n(f)$	power-spectrum estimate of each segment (kPa^2/Hz)
$P_{xx}(f)$	averaged power spectrum (kPa^2/Hz)
PSDF	power spectral density function
RP	recurrence plot
RQA	recurrence quantification analysis
RR	recurrence rate
$R_{i,j}$	recurrence plot matrix
t	time (s)
U	normalizing factor in Welch method
w	window function
$x(i)$	pressure time series
x_i	ith point of space state trajectory
x_j	jth point of space state trajectory
$X(f)$	estimated Fourier Transform
$x(t)$	original signal

Greek letters

ε	radius of neighborhood (threshold for RP computation)
ψ	mother wavelet function
Θ	Heaviside function

proposed to study the complex dynamics of a fluidization system through identifying different scales of structures in the fluidized bed. This technique has found many applications in fluidized beds, for example, chaos analysis of particles (Nie & Lin, 2011), scaling (Briongos & Guardiola, 2005; Rudisuli, Schildhauer, Biollaz, & van Ommen, 2012), studying of nonlinearity (Karimi, Mostoufi, Zarghami, & Sotudeh-Gharebagh, 2011), multi-resolution analysis (Briongos, Aragon, & Palancar, 2007; Zhao & Yang, 2003) and regime transition (Llauro & Llop, 2006). Zhao and Yang (2003) studied three scale components of pressure signals by time delay embedding analysis and demonstrated that the micro scale dynamics is more complex than the meso scale dynamics, and the meso scale dynamics is more complex than the macro scale dynamics.

The concept of recurrence plot (RP) and recurrence quantification analysis (RQA), which relies on the presence of recurring/deterministic structures underlying the data, was recently introduced for the chaos analysis. Recurrence is a basic property of dynamical systems, which can be exploited to describe the behavior of the system in the phase space (Marwan, Carmen Romano, Thiel, & Kurths, 2007; Gandhi, Joshi, Kulkarni, Jayaraman, & Kulkarni, 2008). Tahmasebpour et al. (2013) and Babaei, Zarghami, Sedighikamal, Sotudeh-Gharebagh, and Mostoufi (2012) demonstrated that RP and RQA are potent tools to study fluidization hydrodynamics. However, combination of the multi-scale method and the RQA for studying the complexity of hydrodynamics of fluidized systems has not been developed yet.

Since wavelet analysis has a great potential in signal processing, it has been widely employed in the fluidization field (Johnsson, Zijerveld, Schouten, van den Bleek, & Leckner, 2000; Zhao & Yang, 2003). Accordingly, Daubechies wavelet method was used in this work to decompose pressure signals into sub-signals that represent micro scale, meso scale and macro scale interactions in fluidized beds. Intrinsic complexity of decomposed pressure signals of the three scales was further studied by RP and RQA.

2. Experimental

The experiments were carried out in a gas-solid fluidized bed made of a Plexiglas pipe of 15 cm inner diameter (D) and 200 cm height. Air at room temperature was entered into the column through a perforated plate distributor of 435 holes with 7-mm triangle pitch and its flow rate was controlled by a mass flow controller. A cyclone, placed at the column exit, would return the entrained solids back to the bed. The static bed height (H) in experiments was set to 22.5 cm (H/D = 1.5) and superficial gas velocity was varied in the range of 0.1 to 1.2 m/s. Sand particles (Geldart B) with mean size of 150, 280, and 490 μm and a particle density of 2640 kg/m^3 were used in the experiments.

There are multiple techniques to measure time series signals in fluidized beds such as pressure (gauge or differential pressure), local solids concentration (from optical or capacitance probes), sound (from acoustic probes), vibration (from vibration probes) (Johnsson et al., 2000). Among these methods, pressure fluctuations have been extensively studied for investigation of the hydrodynamics. An attractive advantage of pressure fluctuations is that they are easily measured, even under harsh conditions. The pressure measurement system is robust and relatively cheap. Also, they contain the effect of various dynamic phenomena, such as gas turbulence, bubbles hydrodynamics, and particles behavior, taking place within the system. In addition, other laboratory measurement techniques may not be practical in industrial processes (van der Schaaf, Schouten, & van den Bleek, 1998; Werther, 1999; van Ommen et al., 2011).

Some points should be taken into account in using pressure probes such as dimensioning of the probe-transducer system, proper placement of the probe, sampling frequency, and filtering the signal (van Ommen et al., 2011). However, Croxford, Harrison, and Gilbertson (2005) reported that for a small-scale fluidized bed, in principle, one probe is sufficient to characterize its hydrodynamics. In this work the pressure probe (model SEN-3248 (B075), Kobold Company) was screwed onto the gluing studs located 20 cm (P_4) above the distributor. This probe had a response time of less than 1 ms. The measured signals were band-pass filtered