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Multi-scale analysis of flow structures in fluidized beds with immersed tubes

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ABSTRACT

Multi-scale analysis and non-linear analysis were combined to investigate the hydrodynamics of fluidized beds with and without horizontal tubes. Pressure fluctuations were measured and analyzed employing discrete wavelet analysis, recurrence plot analysis, and recurrence quantification analysis. A systematic procedure was followed to determine wavelet parameters. At low gas velocities, the energy of macro-structures reduces with the addition of the first tube and then increases with the addition of a second tube. However, there is no notable difference at high gas velocities. Determinism is high for the bed without tubes, which can be attributed to the periodic behavior of bubbles. Determinism decreases with the addition of tubes because the breakage of bubbles results in less periodic behavior. The three methods of analysis used in this study captured the effects of immersed tubes on the hydrodynamics of fluidized beds. Recurrence quantitative analysis was found to be a powerful and easy-to-use method that can capture the nonlinear characteristics of fluidized beds much more quickly than conventional methods of nonlinear analysis. This method can thus be effectively used for the online monitoring of hydrodynamic changes in fluidized beds.

Introduction

The characteristics of fluidized beds strongly depend on the bubble behavior and solid flow patterns in the bed. Therefore, understanding different phenomena such as the movement of bubbles, clusters, and particles is important in the design and scaling up of fluidized beds. It has been established that the insertion of horizontal tubes into a fluidized bed affects the bubble behavior (Asegehegn, Schreiber, & Krautz, 2011; Hull, Chen, Fritz, & Agarwal, 1999; Jin, Wei, & Wang, 2003; Kim, Ahn, Kim, & Lee, 2003; Li, Dietiker, Zhang, & Shahnam, 2011; Olowson, 1994; Olsson, Wiman, & Almstedt, 1995; Rahimi & Azizi, 2011; Wiman & Almstedt, 1997). Asegehegn et al. (2011) studied the bubble hydrodynamics of a two-dimensional (2D) fluidized bed with immersed tubes using a digital image analysis technique and showed that the immersed tubes enhanced bubble coalescence and breakage in the bed, leading to the formation of smaller bubbles in the bed. Hull et al. (1999) also observed enhanced bubble coalescence in 2D and 3Dbeds with horizontal immersed tubes. Li et al. (2011) conducted a numerical simulation of such beds and showed that the Eulerian model properly predicts bubble hydrodynamics around a horizontal tube in a bed. Kim et al. (2003) studied the hydrodynamics of bubbles and emulsion around a tube using a fiber optic probe to relate the local heat transfer coefficient to the bubble-tube and emulsion-tube contact times. Hull, Chen, and Agarwal (2000) studied the mixing of solid particles in a 2D bed with immersed tubes and showed that the tube position, gas velocity, and tracer feed location affect the mixing time in gas–solid fluidized beds.

Besides the abovementioned conventional experimental techniques employed to study the complex hydrodynamics of fluidized beds, a quantitative analysis of the hydrodynamics can be conducted by evaluating measured signals (Johnsson, Zijerveld, Schouten, Van den Bleek, & Leckner, 2000; Schouten & Van denBleek, 1998). Time series of different signals can be used to study bed hydrodynamics; e.g., pressure fluctuations (Johnsson et al., 2000; Schouten & Van denBleek, 1998), bed vibration (Abbasi, Sotudeh-Gharebagh, Mostoufi, & Mahjoob, 2009; Abbasi, Sotudeh-Gharebagh, Mostoufi, Zarghami, et al., 2010; Azizpour et al., 2011), acoustic emissions (Karimi, Sotudeh-Gharebagh, Zarghami, Abbasi, & Mostoufi, 2012; Salehi-Nik, Sotudeh-Gharebagh, Mostoufi, Zarghami, & Mahjoob, 2009), and local porosity (Breault, Casleton, & Guenther, 2012; Ellis, 2003; Guenther & Breault, 2007; Moradgholi,

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Nomenclature

a_i	approximation sub-signal (Pa)
d	dimension of the system
DET	determinism (%)
D_j	detailed sub-signal (Pa)
E	total energy of signal (Pa^2)
E_j^a	energy of the approximate sub-signal at level j (Pa^2)
E_j^D	energy of the detailed sub-signal at level j (Pa^2)
j	number of decomposition levels
k	time lag coefficient
n	number of points in a time series
N	size of the recurrence plot matrix
l	length of a diagonal line
$l_{\min}$	predefined minimal length of diagonal lines
L	number of time series divisions
$R_{i,j}$	recurrence plot matrix
RR	recurrence rate (%)
t	time (s)
x	time series of the measured pressure signal (Pa)
x_i, x_j	ith and jth points of the space state trajectory
U_c	turbulent fluidization velocity (m/s)

Greek letters

ε	radius of the neighborhood (threshold for the recurrence plot computation)
ψ	mother wavelet function
Θ	Heaviside function

Mostoufi, & Sotudeh-Gharebagh, 2011). The use of pressure fluctuation signals has advantages over the use of other signals including the ease of measuring and monitoring dynamic phenomena occurring in the bed (e.g., bubble hydrodynamics, particle scale movements, and gas turbulence).

Frequency-domain analysis provides a better view of the bed hydrodynamics than conventional statistical analyses (Parise, Kurka, & Taranto, 2009; Ren, Mao, Li, & Lin, 2001; Sasic, Leckner, & Johnsson, 2007). The fast Fourier transform and power spectral density of pressure fluctuations are used to obtain the dominant frequencies of the phenomena (mostly bubble-related phenomena) occurring in the bed (van Ommen et al., 2011). Employing these methods, better insights into the frequency are obtained while time information is lost. Another method of studying bed hydrodynamics in the frequency domain is multi-scale analysis (Li & Kwauk, 1994). Employing this method, the hydrodynamics of the fluidized bed, which is the outcome of different phenomena, is decomposed into a set of distinct structures at different length scales, namely macro-, meso-, and micro-scales. Macro-structures of high amplitude and low frequency (up to 5 Hz) relate to large-scale phenomena, such as large bubbles and bed surface oscillation. Meso-structures with frequencies in the range of 5–20 Hz relate to clusters and small bubbles and micro-structures of high frequency of 20–200 Hz (Nyquist frequency) relate to the impacts and motions of solid particles and measured noise in the fluidized bed.

Despite its advantages, multi-scale analysis is not robust enough to characterize the highly non-linear dynamics of fluidized beds. Consequently, a combination of multi-scale and non-linear analyses is required to study the non-linear hydrodynamics of fluidized beds. Recurrence plot (RP) analysis and recurrence quantification analysis (RQA) are promising methods of studying non-linear systems. The concepts of the RP and RQA rely on the presence of recurring/deterministic structures underlying the dynamic characteristics of a non-linear system. Recurrence is a basic property of dynamic systems and can be exploited to describe the behavior of a system in the phase space (Gandhi, Joshi, Kulkarni, Jayaraman, & Kulkarni, 2008; Marwan, Carmen Romano, Thiel, & Kurths, 2007). Tahmasebpour, Zarghami, Sotudeh-Gharebagh, and Mostoufi (2013) demonstrated that RP analysis and RQA are effective tools in the study of fluidization hydrodynamics. The effect of horizontal immersed tubes on flow structures has not yet been studied using a combination of the multi-scale method and RQA. Therefore, the main purpose of this article is to apply nonlinear time-series analysis techniques based on the RP and RQA combined with multi-scale analyses to the investigation of the effect of the insertion of horizontal tubes on the flow structures in bubbling gas–solid fluidized beds and to assess if this methodology can accurately describe the hydrodynamics of fluidized beds with immersed tubes. To this end, pressure fluctuations were measured in a laboratory-scale fluidized bed with and without immersed tubes and the multi-scale method and RQA were then employed to track changes of flow structures in the bed.

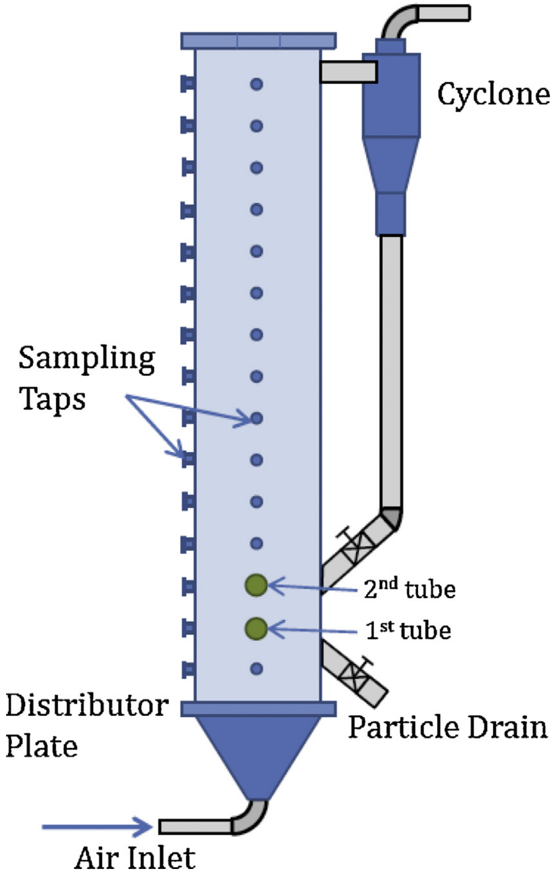

Fig. 1. Experimental set-up.

Experimental

Setup

The experimental setup is shown in Fig. 1. The column was a Plexiglas pipe with an inner diameter of 15 cm and height of 2 m with a cyclone system. The whole system was electrically grounded to minimize electrostatic effects. Air at room temperature entered the column through a perforated plate distributor with 1-mm holes on a 7-mm triangular pitch. The flow rate of air was controlled by a digital mass flow meter. Sand particles with density of 2640 kg/m^3 and mean diameter of 420 μm (Geldart B) were used in the experiments. The height of the static bed was 16 cm in all experiments.