Advanced Powder Technology 23 (2012) 380–386

Contents lists available at ScienceDirect

Advanced Powder Technology

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

Original Research Paper

Investigating the hydrodynamics of gas–solid bubbling fluidization using recurrence plot

Behzad Babaei, Reza Zarghami *, Hossein Sedighikamal, Rahmat Sotudeh-Gharebagh, Navid Mostoufi

Multiphase Processes Department, Oil and Gas Centre of Excellence, School of Chemical Engineering, University of Tehran, P.O. Box 11155/4563, Tehran, Iran

ARTICLE INFO

Article history:
Received 16 March 2011
Received in revised form 1 May 2011
Accepted 11 May 2011
Available online 26 May 2011

Keywords:
Fluidized bed
Recurrence plot
Recurrence quantification analysis
Pressure fluctuation

ABSTRACT

Hydrodynamics of gas–solid fluidized bed was investigated using time series of pressure fluctuations by evaluation of the corresponding recurrence plot (RP). Patterns within RP of the fluidized bed were classified into two groups of local white areas (LWA), showing macro structures, and local bold areas (LBA), showing meso and micro structures. These patterns showed that the fluidized bed system has three different hydrodynamic behaviors as superficial gas velocity increases; at low gas velocities, macro structures become more dominant, further increase in gas velocity empowers influence of finer structures on the hydrodynamic and finally the fluidization regime changes. Additionally, these results were confirmed by recurrence rate (RR) and average cycle frequency. Comparison of RP of the fluidized bed with Lorenz and complete stochastic systems showed that the fluidized bed is more complex than Lorenz system, however, it's hydrodynamic has not stochastic nature.

1. Introduction

Fluidized beds are extensively used in various chemical and physical processes due to their high mass and heat transfer rates. While fluidization has several advantages, its application is accompanied by some difficulties such as sudden and unwanted changes in hydrodynamics, like partial or complete defluidization. Therefore, investigating of on-line monitoring of the fluidized bed hydrodynamics is important from industrial point of view. The hydrodynamics of gas–solids fluidized bed is governed by complex nonlinear dynamic relationships and is mainly controlled by different dynamic phenomena occurring in the bed. Examples of these phenomena are bubble formation, bubble coalescence and splitting, bubbles passage as well as behavior of particles. If the hydrodynamics of the fluidized system is modeled with a set of nonlinear governing equations, a proper understanding of the state of fluidized bed at a certain time can be determined. However, the governing equations of such system are complex and unknown [1]. In this case, a quantitative interpretation of the hydrodynamics of fluidized bed can be achieved through time series evaluation of the measured signals, such as pressure or local void fraction of the bed.

Various nonlinear analysis methods, such as time delay embedding theory, have been used for analyzing the dynamic changes in hydrodynamics of fluidized beds [2–13]. The state of a fluidized bed at a certain time can be determined by projecting all governing variables of the system into a multidimensional space, i.e., the state space. However, it is not possible to determine all governing variables of a fluidized bed. Takens [14] showed that the dynamic state of a system can be reconstructed from the time series of only one characteristic variable such as local pressure in a fluidized bed. A great advantage of pressure fluctuations is that they are easy to measure and include the effect of various dynamic phenomena taking place in the bed, such as gas turbulence, bubbles hydrodynamics and operating conditions of the bed [15]. On the other hand, most of other laboratory measurement techniques are not applicable in industrial processes [16].

While all methods of nonlinear time series analysis are based on the attractor reconstruction of the system in the state space, these methods are accompanied by some limitations such as uncertainty through attractor reconstruction methods [17]. In other words, different reconstruction methods lead to different embedding parameters. Many researchers believe that the two-phase structure of the fluidized bed has a low-dimensional chaotic behavior (typically more than 3 and less than 5) in the state space [5,8,9,18,19]. Thus, attractors with dimensions more than three can be figured only by projection into the two or three-dimensional spaces. On the other hand, long-term data sampling, which is required for typical nonlinear evaluation of the pressure fluctuations in bubbling fluidized bed [18,20,21], is usually involved with some difficulties (e.g., steady sate sampling with practical fluctuation feed flow, data saving, data acquisition, etc.) during experimental measurements. The aim of this work was to apply recurrence plot statistical method to investigate the hydrodynamics of fluidized beds using local

* Corresponding author. Tel.: +98 21 6696 7797; fax: +98 21 6646 1024.
E-mail address: rzarghami@ut.ac.ir (R. Zarghami).

0921-8831/$ - see front matter
doi:10.1016/j.apt.2011.05.002

Nomenclature

$a_{i,j}$	element of distance matrix
DM	distance matrix
d_p	average diameter of particles, μm
f_c	average cycle frequency
L/D	height to diameter of fluidized bed
MDL	main diagonal line
N	number of points used in RP
P	probe position
$R_{i,j}$	recurrence plot matrix
R^d	d-dimensional space
RP	recurrence plot
RQA	recurrence quantification analysis
RR	recurrence rate
U	superficial gas velocity, m/s
U_T	transition superficial gas velocity from bubbling to turbulent regime
x_i	i-th point of space state trajectory

Greek symbols

Θ	Heaviside function
ε	radius threshold
σ	standard deviation, Pa

pressure fluctuation signals. Moreover, a comparison was made with time series from a well-known low-dimensional (three modes) nonlinear deterministic system of Lorenz [22] and a complete stochastic nondeterministic system.

2. Theory

Recurrence plot (RP), introduced first by Eckmann et al. [23], is an easy tool to analyze nonlinear time series, in particular for non-stationary and short-term data. RP can visualize the structures relating to the dynamics of the system [24,25]. While embedding is mandatory for reconstruction of attractor in the state space, RP can be constructed without embedding. All information contained in the embedded RP can be attained in the non-embedded one [26]. While attractors with dimensions more than three cannot be visualized in the state space due to constrains in figuring the high dimensional attractors, any phase space trajectory can be represented in a 2-dimensional plot using RP. Moreover, a remarkable property of RP are its ability to be evaluated based on non-stationary and short-term data [24,25], which can be used in on-line monitoring of fluidization. These features make RP a very potent tool to study fluidized bed hydrodynamics and eliminates needs for time consuming and difficult long-term data sampling required in typical methods of nonlinear analysis, thus, can increase fluidization monitoring ability. While applying nonlinear time series (state space) analysis to experimental time series containing noise is troublesome and the analysis methods in the state space are still subject to research [20], effect of noise can be subsided by changing the value of some RP input parameters [27].

2.1. Mathematical definition of recurrence plot

Recurrence plot is a two-dimensional plot that is defined as [23]:

$$R_{i,j} = \Theta(\varepsilon - \|x_i - x_j\|) \qquad i,j = 1,2,3,\ldots,N \tag{1}$$

where x_i and x_j R^d represent the i-th and j-th points of the d-dimensional state space trajectory, ε is the radius threshold, $\|\ \|$ represents the norm and $\Theta(.)$ is the Heaviside function. The Heaviside function compares any two points of the trajectory. If the norm is less than ε, it is considered as a recurrence point and appears as a black spot in $R_{i,j}$, otherwise, it forms a white spot. In fact, the closed points throughout the trajectory can be visualized through a two-dimensional matrix. In other words, RP shows recurrence states in the phase space. March et al. [26] showed that RP can be constructed without embedding. Therefore, in the present work, the RP of time series of pressure fluctuations was constructed without embedding.

2.2. Recurrence plot construction

Construction of RP is based on evaluation of the distance matrix between the reconstructed points in the phase space. This produces an array of distances in an $N \times N$ distance matrix (DM) where N is the number of points under study. The DM is a matrix whose elements $a_{i,j}$ are equal to the difference of points x_i and x_j [28]. This matrix is converted to RP using radius threshold. Elements of the DM, which are smaller than ε, are considered as recurrence points and form black spots, otherwise they form white spots within RP [28]. Before conversion of DM to RP, the DM can be normalized through dividing each DM element by the mean value of the whole matrix elements.

2.3. Recurrence quantification analysis

Recurrence quantification analysis (RQA) is a method to quantify recurrence plot patterns. The patterns within a RP are related to the dynamics of the system [24]. These patterns are made of recurrence points (single spots). Recurrence rate is the only RQA variable [24,28] that was used in this work.

Recurrence rate (RR) expresses the density of recurrence points throughout the trajectory and is mathematically defined as:

$$RR = \frac{1}{N^2}\sum_{i,j=1}^{N} R_{i,j} \tag{2}$$

where $\sum R_{i,j}$ is the total number of recurrence points.

3. Experiments

The experimental setup is schematically shown in Fig. 1. Experiments were carried out in a gas–solid fluidized bed made of Plexiglas. The column was 15 cm in inner diameter and 2 m in height. During the experiments, air at ambient temperature was entered the column through a perforated plate distributor with 435 holes of 7 mm arranged in a triangular pitch. A cyclone was used to separate particles from air at high superficial gas velocities. Sand particles (Geldart B) with mean size of 150 μm and a particle density of 2640 kg/m^3 were used in the experiments. The experiments were carried out with various initial heights of sand in the bed (L/D of 1 and 1.5) and at gas velocities ranging from 0.1 to 1.2 m/s.

Absolute pressure fluctuations were recorded at different vertical positions through a probe of 50 mm length and 4 mm diameter with a fine mesh net at the side facing of the fluidized bed. The Piezoresistive transducer (Kobold, SEN-3248 B075) used in the experiments had a response time of less than 1 ms. Van Ommen et al. [29] showed that the model of Bergh and Tijdeman [30] pro-