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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

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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).

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