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Recurrence plots to characterize gas–solid fluidization regimes

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ABSTRACT

Recurrence plots have been used to analyze and characterize the investigated fluidization regimes: bubbling, slugging and turbulent. Recurrence plots can be qualitatively analyzed considering the distribution of their local white areas (LWA) and local bold areas (LBA). The LWA reflect the macro-scale structure in the bed and appreciably increase for slugging regime because of the increase of the bubble phase contribution to the fluidization dynamics. On the other hand, the LBA, reflecting meso-scale and micro-scale structures, decreases. Several recurrence quantification analysis parameters (RQA) have been computed for the different regimes analyzed and the most appropriate ones have been chosen to characterize and classify the fluidization regimes. It has been found out that the determinism (DET), the average diagonal length (L), the laminarity (LAM), the trapping time (TT) and the recurrence time of type 2 (RET2) detect the evolution from bubbling to slugging regime. The evolution from bubbling to turbulent regime can be detected with all the investigated RQA parameters. A combination of two RQA parameters gives an excellent classification map which distinguishes the slugging from the bubbling regime.

Introduction

Complex dynamic systems are commonly found in many chemical industry operations. Particularly when the process involves multiphase flow systems, its behavior analysis and its modeling involve additional difficulties due to the interaction between the different phases and the simultaneity of the phenomena taking place.

The gas–solid fluidization has been widely used in industrial applications for many decades in operations where a good contact between the two phases is needed. Gas–solid reaction, solids drying, combustion and gasification are typical applications. Due to its complexity, further study is still needed to improve the efficiency and operation control. Fluidization can operate in different regimes, such as bubbling or turbulent regimes; however, slugging fluidization can also appear. This regime must be avoided because of the amount of gas that does not contact with the solid, thus adversely affecting the operation efficiency.

The fluidization regimes have been studied with several methods, sometimes using sophisticated techniques, such as optical probes (Bai et al., 1997), laser beams (Briongos and Guardiola, 2003) and tomography (Makkawi and Wright, 2002). However, the analysis of pressure fluctuations in the fluidized bed is one of the most popular techniques because the data acquisition is easy to implement, even in industrial facilities, and the analysis of data time series provide abundant and meaningful information.

Since the presence of chaotic behavior in gas–solid fluidization was suggested (Stringer, 1989), the deterministic chaos theory has been developed and used to study gas–solid fluidization and other multiphase flows. Usually, the system state space invariants are computed and analyzed, since they are sensitive to changes in the fluidization regime (van den Bleek and Schouten, 1993; Johnsson et al., 2000; Llop et al., 2012). An alternative procedure can be used to characterize the attractor by computing its dynamic moments (Annunziato and Abarbanel, 1999; Llauró and Llop, 2006).

Recently, an original technique for the nonlinear analysis of pressure fluctuation time series in fluidized beds has been introduced. The recurrence patterns are fundamental characteristics of many dynamical systems. These recurrences, obtained from the phase-space trajectories, can be useful to characterize the system dynamics when properly explored. Eckmann et al. (1987) introduced the recurrence plots (RPs) to visualize the recurrences in two dimensional plots. Zbilut and Webber (Zbilut and Webber, 1992; Webber and Zbilut, 1994) developed the recurrence quantification analysis (RQA) to quantify the RPs morphology.

RPs have been used to study the hydrodynamics of fluidization in bubbling and turbulent regions (Babaei et al., 2012; Tahmasebpour et al., 2013a), to recognize flow regimes in spouted

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beds (Wang et al., 2012) and to monitor the hydrodynamics of gas–solid fluidized beds (Babaei et al., 2013).

In this paper, we analyze the pressure fluctuations of gas–solid fluidization by means of recurrence plots and recurrence quantification analysis. Three different regimes of fluidization have been investigated: bubbling, slugging and turbulent. The morphology of RPs has been analyzed to identify recurrence patterns related to the dynamic structure of the different fluidization regimes. The evolution in each of the regimes has been described with several RQA parameters. Those that are more convenient to characterize and classify fluidization regimes have been selected. The use of these parameters must be done carefully, because misinterpretation can lead to incorrect conclusions.

The aim of this work is to contribute to a better understanding in using this complex technique for the analysis and interpretation of the pressure fluctuations of fluidized beds. Comprehensible maps for the fluidization regime classification with the RQA parameters are introduced.

Background

Deterministic dynamic systems can be depicted in a state space of appropriate dimension so that the sequence of each state generates a trajectory defining the system. If the trajectory is attracted towards a region of the space it becomes an attractor which is characteristic of chaotic systems. Kolmogorov entropy, correlation dimension and Lyapunov exponents have been the most popular invariants used to characterize the attractor. When the system cannot be described with differential equations, the attractor can be reconstructed from experimental time series by using the original data and copies delayed in time (''Embedding theorem'' postulated by Takens, 1981).

Many dynamic systems exhibit a recurrent behavior and the recurrence of the states is a fundamental and typical property of nonlinear systems. Hence, a way to analyze the nonlinear system is to characterize the intrinsic pattern of repetition of state space trajectories with recurrence plots.

Recurrence plots

As pointed out above, the attractor of a system can be reconstructed from time series of experimental data. In this case, the pressure fluctuations of the fluidized bed,

$$\vec{x}(t) = \{x(t_1), x(t_2), x(t_3), \ldots, x(t_n)\} \quad (1)$$

From the original data the state space vectors can be obtained,

$$\vec{y}_i(t) = \{x(t_i), x(t_{i+\tau}), x(t_{i+2\tau}), \ldots, x(t_{i+(m-1)\tau})\} \quad (2)$$

where τ is the delay and m the embedding dimension, which must be carefully selected. The set of equation vectors (2) define the reconstructed attractor. The delay can be obtained from the minimum of original time series mutual information and the minimum embedding dimension by the method of the False Nearest Neighbours (Abarbanel, 1996). Obviously, for dimensions higher than three the visualization of the state space trajectory (attractor) becomes very difficult.

Recurrences of the phase space trajectory can be visualized in a two dimensional plot using the tool called Recurrence Plot (RP) which is independent of the trajectory dimension (Eckmann et al., 1987). The recurrence concept is very easy: the recurrence for a time series is when a point of the trajectory repeats itself. Repetition means that a point is close enough to another one within an interval of error suitably selected.

An RP is generated from the reconstructed attractor by computing the matrix $R_{i,j}(\varepsilon)$ whose mathematical definition is:

$$R_{i,j}(\varepsilon) = \Theta(\varepsilon - \|\vec{y}_i - \vec{y}_j\|) \quad i,j = 1,2,3,\ldots,N \quad (3)$$

where N is the number of considered states in the space state $(\vec{y}_i)$, $\vec{y}_i$ and $\vec{y}_j \in R^d$ are two different points of the space trajectory, ε is a threshold or radius of neighborhood, $\|\cdot\|$ represents the norm and Θ the Heaviside function $\Theta(h) = \{1|h > 0; 0|h \leqslant 0\}$. In other words, the generated matrix can be defined as:

$$R_{i,j}(\varepsilon)\begin{cases} 1: & \vec{y}_i \approx \vec{y}_j, \\ 0: & \text{otherwise} \end{cases} \quad i,j = 1,2,\ldots,N, \quad (4)$$

$\vec{y}_i \approx \vec{y}_j$ means that the states are the same within an error or inside a threshold distance ε. Thus the matrix indicates when the state of the system is similar. From the $N \times N$ matrix of black and white dots a two time-axes recurrence plot can be plotted. Recurrence plots are useful to characterize the data and to find transitions and interrelations. A RP has always a black main diagonal line, the line of identity (LOI). Furthermore, from Eq. (3) it is apparent that the RP is symmetric with respect to the main diagonal.

The threshold radius ε is an essential parameter to generate RPs. If ε is too small, no recurrence points are detected and no useful information will show up. On the other hand, if ε is too large, even consecutive points of the trajectory may be considered a recurrence. Several criteria have been proposed in the literature to select this parameter (Marwan, 2011). In this work the guidelines of Zbilut et al. (2002) and Zbilut and Webber (2006) has been used.

Concerning the embedding dimension, several authors suggest that it does not have a determining effect on the quantification of the RP and, hence, any value can be chosen for this purpose (Iwanski and Bradley, 1998; March et al., 2005). These authors suggest that the embedding dimension can be just 1 if the data are to be analyzed with RQA, which means that no embedding is actually needed. About the delay, Webber and Zbilut (2005) advocated that it is not a critical parameter and it can be chosen to be 1.This fact makes it easier to analyze the time series by RPs. In this paper both the dimension and the delay have been chosen accordingly to these recommendations

Patterns

The whole structure of the black points in the RPs can configure different geometric typologies. Marwan et al. (2007) pointed out several different qualitative structures. They are called *homogeneous* when the uniformity is observed in all the zones of the RP; as is typical of stationary systems; *periodic*, if the plot has several diagonal lines and the structure of local zones is repeated to complete all the RP; *drift,* when there is a slow variation of the parameters, typical of non stationary systems, and the black points density decreases from the main diagonal*; disrupted,* when sudden changes occur in the dynamics of the system, originating wide areas of white points.

If smaller scale structures are considered, the plot shows different behavior characteristics. Single points are present when the system does not persist or strongly fluctuates. Diagonal lines mean that some segment of trajectories runs parallel to other segments. Diagonal lines parallel to the LOI are due to the evolution of states which are similar at different epochs. The process can be deterministic if these diagonal lines are present beside single isolated points; the process can be chaotic if these diagonal lines are periodic, meaning that unstable periodic orbits exist. Horizontal or vertical lines are originated when for a certain time there is no change in the trajectory or it is very slow (indicating of laminar states).

Babaei et al. (2012) classified the patterns of the recurrence plots of pressure fluctuations of gas–solid fluidization into two groups; the local white areas (LWA) and the local bolt areas