Online Detection of Hydrodynamic Changes in Fluidized Bed using Cross Average Diagonal Line

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Abstract

Online detection of hydrodynamics of gas-solid fluidized bed was characterized using pressure fluctuations by cross recurrence plot (CRP) and cross recurrence quantification analysis (CRQA). Experiments were conducted in a lab scale fluidized bed of various particle sizes 150 μm, 280 μm and 490 μm at different gas velocities. Firstly, pattern changes of cross recurrence plot were discussed and then reference states was selected. Afterwards, cross average diagonal line (*CLave*) of other states corresponding to reference states were obtained. It was found that cross average diagonal line of non-normalized data initially decreases and then increases with increasing the gas velocity. When the signal is initially normalized, cross average diagonal line does not change with the superficial gas velocity. It was concluded that cross average diagonal line could be used for detecting small changes of particle size and if a proper reference state is chosen, it can be perceived as a powerful index for detecting changes in the size of particles in a fluidized bed.

Keywords

Cross recurrence quantification analysis;
Fluidized bed;
Cross average diagonal line;
Pressure fluctuations;
Online detection.

1. Introduction

Gas-solids fluidized beds are extensively used in the industries owing various multiphase flow such as petroleum, petrochemical, chemical, mineral, biochemical, pharmaceutical, food, etc. The wide application of fluidized beds is due to their high efficiency of mass and heat transfer, thermal homogeneity, high mixing ability and effective contact between solid and fluid [1]. Fluidized bed reactors are among the most complex unit operations due to nonlinear dynamics of the two-phase flow. As a result, modeling the hydrodynamics of these reactors are a challenge due to the complexity of their governing equations [2]. Pressure fluctuation of the gas inside the bed is an essay to measure variable process that includes information about many different dynamic phenomena occurring in the bed. These include gas turbulence, bubbles hydrodynamics and the effect of bed operating conditions [3, 4].

Several methods can be used for analyzing the time-series in the state space [5-10]. In these analysis methods, dynamical systems are analyzed by comparison of their attractors in the state space

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[11] with the help of statistical methods such as S-statistic [12] and Z-statistic [13]. The main drawbacks of these methods are long-term data requirement, time-consuming calculations and uncertainty in determination of embedding parameters [14]. Recently, several researchers have utilized the recurrence plot (RP) to analyze the nonlinear time-series. The concept of the RP and recurrence quantification analysis (RQA) was introduced by Eckmann et al. [2, 15] and developed to describe the behavior of the system in the phase space. Hydrodynamics of fluidized bed was also investigated by RP and RQA and it was shown that the RP is a powerful and easy method for monitoring and detecting changes of the flow patterns in a fluidized bed [16]. The online monitoring of hydrodynamic status of a fluidized bed was explored using RP and its capability to predict sudden changes was compared with the S-statistic method which revealed its high sensitivity [17]. Also, Sedighikamal et al. [18] used one of CRQA parameters to show ability of this method to investigate the velocity transition. Tahmasebpoor et al. [19] investigated the hydrodynamics of fluidized beds by RP and showed its advantage in comparison to statistical and wavelet transform techniques.

In this work, monitoring method based on the cross recurrence plot (CRP) proposed by Marwan et al. [20], as a bivariate extension of RP, is applied to online detection of hydrodynamics of bubbling fluidized beds through measurement of bed pressure fluctuations. Effect of superficial gas velocity and particle size on the hydrodynamics of the bed is investigated with cross average diagonal line (*CLave*).

2. Theory

2.1 Recurrence Plot

Recurrence plot was first introduced by Eckmann et al. [15]. This technique is a method to visualize the recurrences of a dynamical system. A RP prepares a qualitative pattern of the time-series correlations over all available time scales. This method can be used for non-stationary and short-term data. An advantage of this method is that it does not need embedding parameters and all information can be extracted from the non-embedded signal [21].

RP is a two dimensional plot extracted from a distance matrix and can visualize structures of the dynamics of the system [22]. The distance matrix is an $N \times N$ matrix whose elements are determined based on the distance between points $\vec{x}_i$ and $\vec{x}_j$ in the phase space. For construction of RP, a radius threshold is specified and the plot is defined as:

$$R_{i.j}(\varepsilon) = \Theta\left(\varepsilon - \left\|\vec{x}_i - \vec{x}_j\right\|\right). \qquad i.j = 1.\dots.N \tag{1}$$

where N is the number of measured points, $\vec{x}_i$, ε is threshold distance, $\Theta(.)$ is the Heaviside function and |.| is a norm for indicating the difference between trajectories. The Heaviside function is a tool for comparing two trajectories. If difference of each trajectories is greater than ε the Heaviside function will be equal to zero, $R_{i,j}(\varepsilon)=0$. In opposite, if the distance is less than ε, the Heaviside function will be equal to one, $R_{i,j}(\varepsilon)=1$. For plotting this matrix, a black dot is shown where $R_{i,j}(\varepsilon)=0$ and a white dot where $R_{i,j}(\varepsilon)=1$. According to its definition, RP is a symmetric plot and its main diagonal is black. According to this definition, each point shows the recurrences of dynamical system states.

2.2 Cross Recurrence Plot

CRP is an extension of RP which is capable of analyzing dependencies of two dynamical systems in all times by comparing their states [20]. The CRP investigates the dynamics of two systems in one phase space and then displays it into a plot. The cross recurrence matrix is defined as:

$$CR_{i.j}^{\vec{x}_i.\vec{y}_j}(\varepsilon) = \Theta\left(\varepsilon - \left\|\vec{x}_i - \vec{y}_j\right\|\right). \qquad i = 1.\dots.N\ ;\ j = 1.\dots.M \tag{2}$$

where N is the number of first measured variable $\vec{x}_i$ and M is the number of second measured variable $\vec{y}_i$. In the CRP, the length of measured variables, $\vec{x}_i$ and $\vec{y}_i$, are not to be necessarily equal. However, in the present work, N and M were considered to be equal and the trajectories on phase space were constructed based on the time-series for both systems. Due to the difference in the two systems, the main diagonal of CRP is not entirely black and the plot is not symmetric. Moreover, according to this definition a black dot in the CRP is not an indication of the recurrence of system but declares the similarity states between the two systems.

2.3 Cross Recurrence Quantification Analysis

Quantification of CRP structures is performed by applying the CRQA. The CRQA determines how and how often the two systems show similar patterns of change or movement. CRQA parameters are defined such that they would have a physical interpretation. Some of these parameters are defined based on the diagonal structures and are used for articulating the coordination of two systems. One of these parameters is cross average diagonal line (*CLave*) which represents the average amount of similarity states between trajectories of the two systems and the time that both systems stay attuned. This parameter is defined as:

$$CLave = \frac{\sum_{l=L_{\min}}^{N} lP(l)}{\sum_{l=1}^{N} P(l)} \tag{3}$$

where *P(l)* is the number of diagonal line of length *l*.

Cross recurrence analysis was done for both normalized and non-normalized signals.

The signal was normalized as follows:

$$S_n = \frac{S_i - \mu_S}{\sigma_S} \tag{4}$$

3. Experiments

Experiments were conducted in a column made of a Plexiglas pipe of 15 cm inner diameter and 2 m height. The experimental setup is schematically shown in Fig. 1. Air enters the column at ambient temperature through a perforated plate distributor with 435 holes of 1.7 mm diameter arranged in a 7 mm triangular pitch. Gas flow rate was measured and controlled by a mass flow controller (MFC). A cyclone was utilized to separate particles from air at high superficial velocities and return them back to the bed. The initial aspect ratio of solids in all experiments was one.

A pressure probe (Piezoresistive transducer, Kobold Co., SEN-3248 B075) was used to measure pressure fluctuations of the bed at 10 cm above distributor. This probe had a response time of less than 1 ms. Absolute pressure fluctuations were recorded through a probe of 50 mm length and 4mm diameter with a fine mesh on its tip. The measured signals were band-pass filtered (hardware) at lower cut-off frequency of 0.1 and upper cut-off Nyquist frequency of 200 Hz. The pressure transducer was connected to a 16-bit data acquisition board (Advantech 1712L). The filtered signals were then amplified with a gain of 100. In order to satisfy the Nyquist criterion the sampling frequency for pressure fluctuation signals was adjusted to 400 Hz. The sampling frequency used in this work was 50 to 100 times more than the average cycle frequency which is required for nonlinear evaluation of the pressure fluctuations in bubbling fluidized bed [23, 24].

Table 1. Properties for particles.

Mean particle size (μm)	Density (kg/m^3)	U_{mf} (m/s)	U_c (m/s)
150	2640	0.029	0.9
280	2640	0.059	1.1
490	2640	0.182	1.3

Experiments were carried out with different Geldart B particles. For each sample 65535 data points were recorded which corresponding to about 164 seconds of sampling time. Size, minimum fluidization velocity (calculated using Wan and Yu Equation [25]) and velocity of onset of turbulent fluidization (calculated using standard deviation) of these particles are given in Table 1. Different superficial gas velocities in the range of 0.03 m/s to 1.2 m/s were used in the tests.

4. Result and Discussion

4.1 Cross recurrence plot

Hydrodynamics of fluidized beds could also be studied by the CRP method. The CRP of normalized pressure fluctuations of the fluidized bed considered in this work, is shown in Fig. 2 for different particle sizes at 0.3 m/s superficial gas ve-

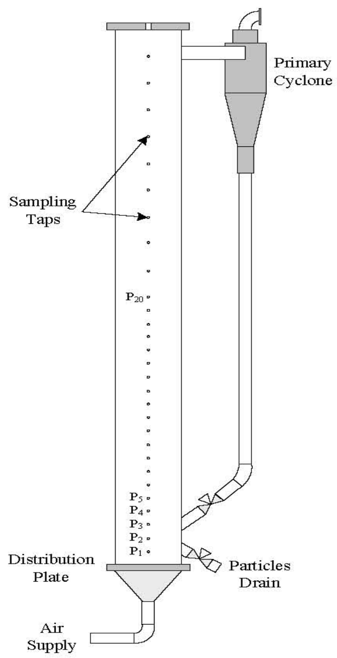

Figure 1. Schematic view of the experimental setup. P1, P2, … are sampling taps.

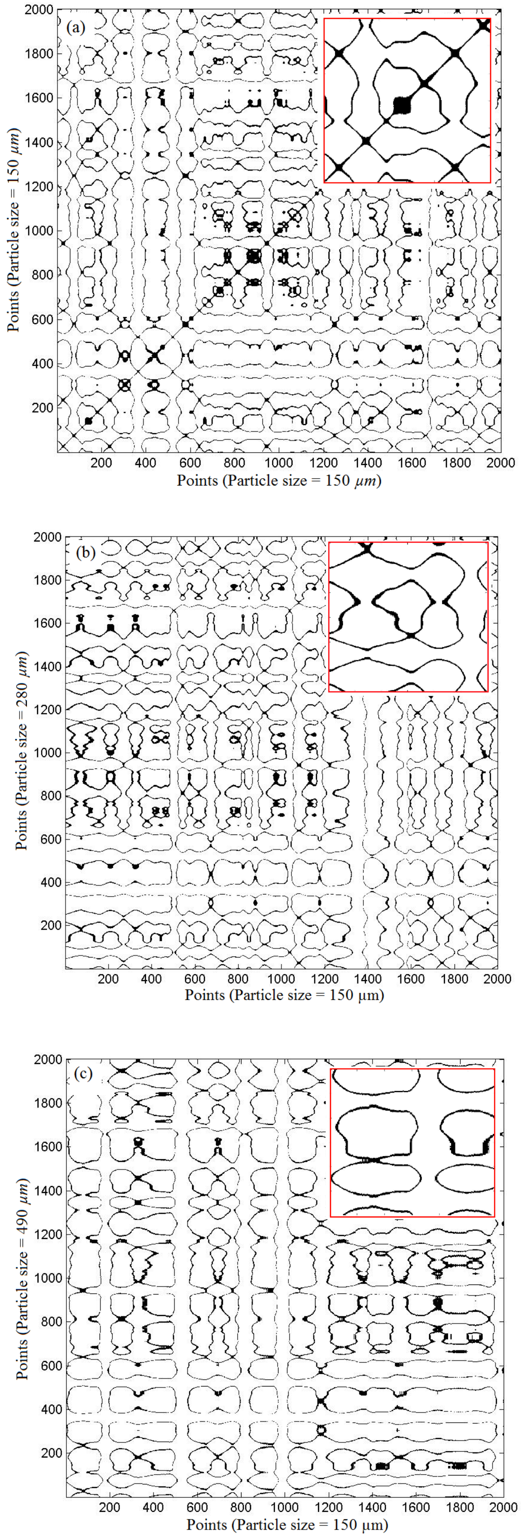

Figure 2. Cross recurrence plots pressure fluctuations of different states of the fluidized bed with different particle size at 0.3 m/s superficial gas velocity; (a) both 150 μm, (b) 150 μm and 280 μm, and (c) 150 μm and 490 μm. All plots were drawn using 2000 points of normalized signals and threshold of 0.08.

locity. Here, pressure fluctuation of the bed of 150 μm particles was considered as the reference signal. Radius threshold ε=0.01 and 2000 data points as the epoch length were used to construct the cross recurrence matrix. The CRP of the fluidized bed system with the same particle size (150 μm) and the same superficial gas velocity (0.3 m/s) is shown in Fig. 2(a). As mentioned previously, the CRP becomes a RP when two identical signals are used in Eq. (2). As expected, the LOI (line of identity) or main diagonal line of RP are completely seen in this figure. Fig. 2(b) demonstrates the CRP of pressure fluctuations of two different states of the bed. While the first signal is measured at particle size of 150 μm and superficial gas velocity of 0.3 m/s, the second signal is obtained from the bed of 280 μm particles and 0.3 m/s superficial gas velocity. It can be seen in this figure that the LOI is disrupted and density of diagonal structures is less than in the RP. Fig. 2(c) shows the CRP of the bed with 150 μm and 490 μm particles. There is no pattern similar to the RP in this figure. Therefore, it can be concluded that the CRP can detect hydrodynamic similarities and differences between two states of the bed. It can be seen in Fig. 2 that single dots are rarely present in the CRP of the fluidized bed which demonstrates their non-stochastic nature. Therefore, the fluidized bed behaves between stochastic (chaotic) and predictable (periodic system as a regular one) systems. This result has also been proven by recurrence analysis and it has been confirmed that dynamical behavior of fluidized beds is placed between stochastic and predictable systems [16].

4.2 Cross Recurrence Quantification Analysis

Input parameters (i.e., embedding dimension, time delay, minimum length of diagonal line and radius threshold) and length of epoch should be specified for analyzing the pressure signals of fluidized beds by CRQA. Prior to parameter selection, the length of epoch (N) for the CRQA calculations should be discussed. The effect of number of data points has been investigated in Fig. 3 and it was concluded that CRQA variable studied in this work do not change considerably for N bigger than 2000. This shows that CRP method gives useful information with low amounts of data, concluding that it is a powerful and easy method for fluidized bed analysis. Effect of changes in Embedding dimension and time delay parameters were studied in this work but there were not radical differences in the results. Therefore, embedding dimension of 2 and time delay of 1 were selected. Most researchers have indicated that typical value of the minimal

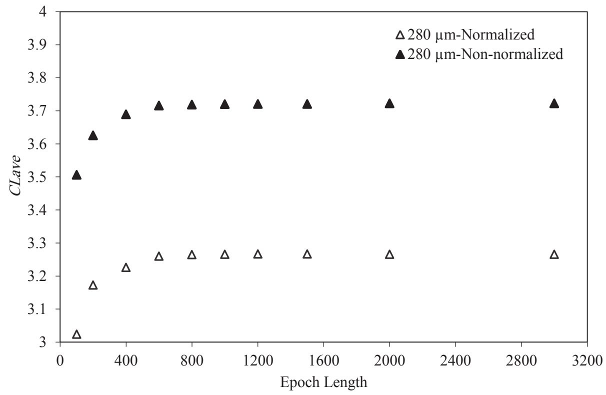

Figure 3. Cross average diagonal line of cross recurrence plot of different states within the fluidized bed as a function of epoch length. Pressure fluctuations of the fluidized bed of size 150 μm particles were considered as the reference. U=0.5 m/s; ε=0.08 and ε=0.01 are considered for normalized signal and non-normalized signal respectively.

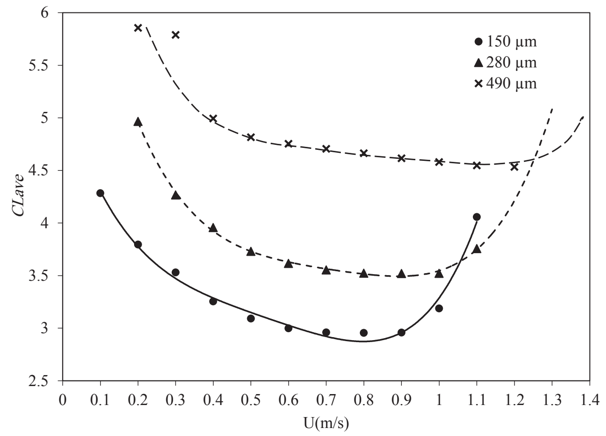

Figure 4. Cross average diagonal line of cross recurrence plot of two states of the bed as a function of superficial gas velocity. Pressure fluctuations at U/Umf=1.5 is considered as the reference signal. Epoch length=2000 points, ε=0.01, and total length of time series=65535 points. Signal is non-normalized.

length of diagonal line is (Lmin) 2 [19, 26, 27]. Accordingly, the optimum values of minimal length of diagonal lines have been chosen to be 2. The last input parameter is the radius threshold (ε), which determines the number of points appeared in the cross recurrence plot. In this work, the suitable radius threshold, based on the method proposed by Webber and Zbilut [28], was obtained ε=0.01 for non-normalized and ε=0.08 for normalized signal.

To explore the ability of CRQA in detecting similarities in different states of system, one of the quantitative parameters that can reveal changes in particle size and superficial gas velocity was exploited. Cross average diagonal line of CRP of two time series with different superficial gas velocities is shown in Fig. 4. As can be seen in this figure, when data are not normalized, CLave changes with changing in the superficial gas velocity. In fact, *CLave* decreases with increasing the superficial gas velocity since decreasing the attunement time of two time series results in smaller *CLave*. Nevertheless, the *CLave* increases at higher gas velocities. This change in the trend occurs at 0.8-0.9 m/s, 1.0-1.1 m/s and 1.2-1.3 m/s, respectively, for 150 μm, 280 μm and 490 μm particles. These velocities coincide with the transition from bubbling to turbulent fluidization regime. In fact, by increasing the superficial gas velocity in the bubbling regime, bubbles (macro-structures) increase in the bed (i.e., more heterogeneity) which results in decreasing similarities of the two time series. This trend continues until the largest possible bubbles are formed in the bed, i.e., at the onset of turbulent fluidization. On the other words, *CLave* decreases because of decreasing attunement time of the system state with reference signal. Beyond this velocity, bubbles (macro structures) transform into voids (meso structures) and the share of macro structures decreases in the hydrodynamics of the bed after transition to turbulent regime. On the other words, dynamics of system changes and *CLave* increases while velocity transition is occurred. In fact, the fluidized bed in the turbulent regime is more homogeneous than in the bubbling regime.

Sensitivity of CRQA parameters to change in the superficial gas velocity can be decreased by normalizing the signals. Fig. 5 shows *CLave* of CRP between two states of the fluidized bed as a function of superficial gas velocity using normalized pressure fluctuations. In this figure, pressure fluctuations signal at *U*=0.9 m/s (as specified with dash line) was considered as the reference. It can be seen in Fig. 5 that *CLave* of normalized signals change very gradually against superficial gas velocity. This demonstrates that this parameter is not sensitive to small variations of superficial gas velocity.

Effect of particle size on CRQA of pressure fluctuations of fluidized bed was also investigated in this work. Fig. 6 shows the variation of *CLave* as a function of particle size at various gas velocities. Normalized pressure fluctuations of the bed of 150 μm particles were considered as the reference signal. It can be seen in this figure that *CLave* decreases with increasing the particle size. The *CLave* at 150 μm particle size is related to attunement time of the system (obtained from the RP). *CLave*

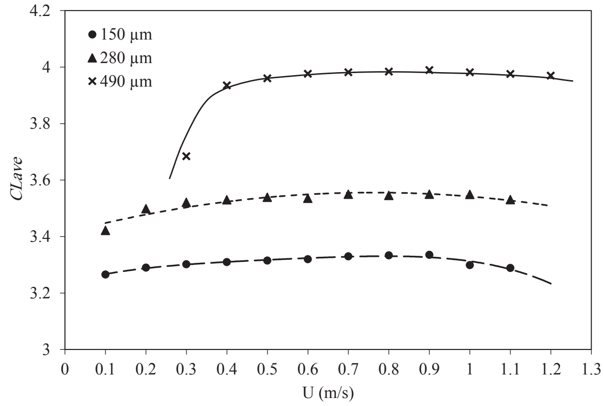

Figure 5. Cross average diagonal line of cross recurrence plot of two systems as a function of superficial gas velocity. Pressure fluctuations at superficial gas velocity 0.9 m/s is considered as the reference signal. Epoch length=2000 points, ε=0.08, total length of time series=65535 points. Signal is normalized.

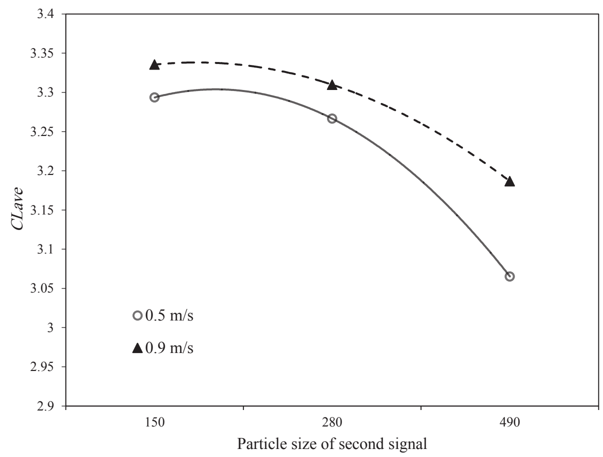

Figure 6. Cross average diagonal line of CRP between two states as a function of particle size. In all cases, state with particle size 150 μm is considered as the reference. Epoch Length=2000 points, total length of time series=65535, ε=0.08. Signal is normalized.

of the system with 280 μm particle size is related to attunement time of CRP between two states of the system with different particle sizes (150 μm as reference state and 280 μm as the evaluating one) and the same superficial gas velocity. It can be seen that *CLave* at 280 μm is slightly less than that one at 150 μm, but the difference is not meaningful. When particle size increases to 600 μm, change of *CLave* is considerable. This shows that *CLave* can detect particle size changes in fluidized bed.

5. Conclusion

CRQA method is a powerful tool to online detection of hydrodynamic status of a gas-solid fluidized bed. CRP of pressure fluctuation of the fluidized bed at various experimental conditions was obtained and the bed hydrodynamics changes were detected by cross average diagonal line. It was concluded that in the bubbling regime of fluidization, average similarities of the systems decrease with increasing the superficial gas velocity. However, cross average diagonal line increases in the turbulent regime which indicates that the bed becomes more homogeneous in this condition. It was shown that cross average diagonal line of normalized signal is not sensitive to changes in the superficial gas velocity which is beneficial to detect the changes in particle size. Also, it was shown that cross average diagonal line can detect the change of mean particle size in the bed and it varies significantly even if the signal is normalized.

Nomenclature

CR	Cross recurrence matrix between two phase space trajectories
CR_{ij}	Cross recurrence point
CRP	Cross recurrence plot
CRQA	Cross recurrence quantification analysis
Clave	Cross average diagonal line
DM	Distance matrix between phase space vectors
i,j	Indices
Lmin	Minimum diagonal line length
L	Diagonal line length
M	Embedding dimension
M	Number of data points for second signal
N	Number of data points for first signal or reference signal
Nl	Number of diagonal line
P(l)	Number of diagonal line of length *l*
R	Recurrence matrix between two phase space trajectories
Rij	Recurrence point
Sn	Normalized signal
Si	Non-normalized signal
U	Superficial gas velocity (m/s)
U_c	Velocity transition from bubbling to turbulent regime (m/s)

U_{mf}	Minimum fluidization velocity (m/s)
$\vec{x}_i$	First time series
$\vec{y}_i$	Second time series

Greek letters

Θ	Heaviside function
ε	Threshold radius
σ	Standard deviation
μ	Mean of time-series

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