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Using S-statistic for investigating the effect of temperature on hydrodynamics of gas–solid fluidization

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ABSTRACT

The influence of temperature on fluidization was investigated by a statistical chaotic attractor comparison test known as S-statistic. After calibration of the variables used in this method, the S-test was applied to the radioactive particle tracking (RPT) data obtained from a lab-scale fluidized bed. Experiments were performed with sand as fluidized particles and in temperatures from ambient up to 600 °C with superficial gas velocities of 0.29, 0.38 and 0.52 m/s. Considering the behavior of bubbles and comparing with frequency domain analysis, it was concluded that S-statistic is a reliable method for characterization of fluidization process behavior at different temperatures.

1. Introduction

Many chemical processes, such as coal gasification and combustion, are carried out in high temperature gas–solid fluidized beds. Although temperature directly affects mass transfer and reaction rates in the bed, most investigations on fluidized bed hydrodynamics are limited to ambient temperatures. Lack of accurate knowledge of high temperature hydrodynamics can be attributed to difficulties associated with measuring techniques. Cui, Sauriol, and Chaouki (2003) studied the effect of temperature on local two-phase flow structure. Rapagna, Foscolo, and Gibilaro (1994) investigated the quality of fluidization of three powders in a gas–solid fluidized bed. The influence of temperature on minimum fluidization velocity was investigated by Subramani, Balaiyya, and Miranda (2007).

In spite of the above mentioned studies, there is still need for fundamental studies at high temperatures using robust and reliable measurement techniques. Effect of temperature on solid phase mixing and phase dynamics of FCC powder was studied by Cui et al. (2003) and Cui and Chaouki (2004) using optical fiber probe to measure instantaneous particle concentration in the fluidized bed. X-ray technique, which provides a moving image of the internal flow patterns of fluids and solids inside a vessel, was used by Lettieri, Yates, and Newton (2000) for investigating fluidization behavior at elevated temperatures. Doucet, Bertrand, and Chaouki (2008) showed radioactive particle tracking (RPT) technique as an accurate, non-intrusive method for monitoring the motion of solid particles in fluidized bed.

Recently many investigators (Bai, Bi, & Grace, 1997; Zarghami, 2009) showed that fluidized beds exhibit chaotic behavior. The embedding theorem has been utilized to reconstruct attractors which describe the fluidization process. Diks, van Zwet, Takens, and De Goede (1996) combined this reconstruction with a statistical test to determine the statistical changes between two different time series. van Ommen, Coppens, van den Bleek and Schouten (2000) presented an enhanced monitoring method based on the statistical test developed by Diks et al. (1996) and comparison of attractors for monitoring small changes in the bed and detecting agglomeration in early stages. Also, Shiea, Sotudeh-Gharebagh, Azizpour, Mostoufi, and Zarghami (in press) applied this attractor comparison to vibration signals of a fluidized bed for predicting the onset of the turbulent regime. In the present work, the RPT technique was used for characterization of the hydrodynamics of gas–solid fluidized bed due to its excellent performance under severe conditions at high temperatures. Comparing reconstructed attractors in state space was used to obtain more information on the effect of temperature on fluidization hydrodynamics.

2. Theory

The S-statistic test provides a criterion for the comparison of reconstructed delay vectors coming up from a stationary state

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Nomenclature

ACF	autocorrelation function
d	bandwidth
E	energy of the signal
E_{WB}	wide band energy
f_{N}	Nyquist frequency (Hz)
l	segment length
m	embedding dimension
N	total number of samples
N_{f}	number of points in the frequency domain
P_{xx}	power spectrum (mm^2/Hz)
$\hat{Q}$	unbiased estimator
S	S-statistic value
T_{w}	time window (s)
V_{C}	conditional variance of delay vector
x_i	sample of time series
$\bar{x}$	mean
X_i	normalized time series

Greek letters

σ_x	standard deviation
Δf	frequency resolution (Hz)
Δt	sampling time (s)
τ	embedding time delay

in a multidimensional pseudo steady state system (Diks et al., 1996). Two separate time series, known as reference and evaluation time series, can be considered as samples of attractors which describe the behavior of a system at two distinct states. In the case of a fluidized bed, most investigators (e.g., Chaplin, Pugsley, & Winters, 2005; van Ommen et al., 2000) used pressure fluctuations time series. They considered the null hypothesis for comparing delay vectors to examine whether or not they arise from the same sources.

The S-statistic, which represents the statistical differences between these states, is calculated using the following equation (Diks et al., 1996):

$$S = \frac{\hat{Q}}{\sqrt{V_{\mathrm{C}}(\hat{Q})}}, \tag{1}$$

where $\hat{Q}$ is the unbiased estimator of squared distance between two distinct time series and V_{C} shows the conditional variance of delay vectors under the null hypothesis and is used for normalizing the estimator. By assuming the null hypothesis that the two sets of probability distributions of delay-vectors have the same origin, the random variable S has a mean value of zero and a standard deviation of 1. Diks et al. (1996) showed that if S value is greater than 3, the null hypothesis is rejected with a confidence level of more than 95%; thus, the two sets are generated by different dynamic mechanisms.

Four key parameters in this algorithm are time delay (τ), embedding dimension (m), bandwidth (d) and segment length (l), which strongly affect the performance of the method and should be chosen optimally. These parameters and their identification procedure are discussed below.

2.1. Time delay

To construct an attractor from an experimental time series using the method of time delay, the attractor vector is produced from the discretely sampled time series with a discrete delay increment. There are various methods for determining an optimum for this discrete segment length. The autocorrelation function was used in this work for selecting the time delay. In the present work, the appropriate time delay was selected as the first value of the delay for which the autocorrelation function becomes equal to one-half (Zarghami, Mostoufi, & Sotudeh-Gharebagh, 2008). The autocorrelation function (ACF) compares two data points in the time series separated by delay τ and is defined as:

$$\mathrm{ACF} = \frac{\sum_{i=1}^{N-\tau}(x_i')(x_{i+\tau}')}{\sum_{i=1}^{N-\tau}(x_i')^2}, \tag{2}$$

where

$$x_i' = x_i - \bar{x}_i. \tag{3}$$

2.2. Embedding dimension

In the method of time delay, the attractors are embedded in an m-dimensional space. This number of elements of the reconstructed state vector is known as the embedding dimension. Several methods exist for determining the embedding dimension, for instance, the method of time window. As shown by Zarghami (2009), in this method, after specifying an optimum value for the time window T_{w}, the embedding dimension (m) can be calculated as:

$$m = \frac{T_{\mathrm{w}}}{\tau \Delta t}. \tag{4}$$

Zarghami (2009) also mentioned that for attractors with a dominant periodic characteristic, the optimum value for the time window can be chosen equal to the average cycle time, which is defined as the length of the time series (in time units) divided by the number of cycles. It should be noticed that in the time window method, to calculate the embedding dimension, τ is usually considered equal to 1. (Zarghami, 2009).

2.3. Bandwidth

Bandwidth (d) is another key parameter in the S-statistic algorithm that sets the Gaussian kernel smoothing length scale. Diks et al. (1996) reported that the bandwidth can accept a wide range of possible values. However, the accuracy of the S-statistic test strongly depends on optimal choosing of this parameter. Diks et al. (1996) showed that by selecting a small value for d, the test will pick up local differences between the two distributions and poor statistics will be obtained. This result can be observed from the behavior of the unbiased estimator ($\hat{Q}$) when limiting d toward zero. For a large bandwidth, however, the delay vector distributions would be smoothed to such extent that they become almost indistinguishable. The optimal value of the bandwidth can be achieved by keeping a balance between these two effects, and it is affected by the number of observations (Diks et al., 1996). The observation which was used in this work is based on calculating the S-value for some different combinations of time series at various bandwidth values. Then the bandwidth which gives a maximal value of S will be chosen as the optimal value of d.

2.4. Segment length

Segment length (l) is the last parameter used in the S-statistic test which is applied to remove dynamic correlations between successive points in the state space. According to Diks et al. (1996), selecting a small value for the segment length results in that the S-statistic value will significantly differ from 0 with a larger standard