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Original Research Paper

Dynamic analysis of the scale-up of fluidized beds

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ABSTRACT

A method is developed for hydrodynamics scale-up of gas-solid fluidized beds based on recurrence quantification analysis of nonlinear time series of pressure fluctuations. This method is an improvement of the previous method by including the entropy of pressure fluctuations to the list of scale-up parameters. Experiments were carried out at varying conditions, e. g., bed diameter (5, 9, 15, 40 and 80 cm ID), particle size (150, 300, 400 and 600 μm), bed height at aspect ratios (1, 1.5 and 2) and superficial gas velocities (ranging 0.1 to 1.7 m/s) to identify the main parameters that influence the dynamics and to develop a general interpretation of the analysis results. By investigation of the effect of operating parameters on entropy, a quantitative empirical correlation is proposed for including the entropy in the scale-up parameters. It was shown that this correlation improves the Glicksman's method for the scale-up of fluidized beds.

1. Introduction

Scale-up of fluidized beds has always been an obstacle in widespread use of these reactors in industry. This difficulty arises from the fact that the hydrodynamics of fluidized beds is very complex and, especially, the effect of bed diameter is still not very well understood. Proper description of the hydrodynamics of gas-solid fluidized beds is difficult since fluidized beds are a heterogeneous mixture of gas and solids exhibiting a liquid-like behavior [1]. Considering that scale-up deals with the hydrodynamics, having no detailed understanding of the hydrodynamics of fluidized beds is believed to be one of the key reasons for the difficulties encountered in design and scale-up of fluidized beds [2]. Therefore, detailed understanding of their hydrodynamics can definitely improve the scaling. The hydrodynamics of gas-solid fluidized beds are usually studied using time series evaluation of the measured signals [3,4]. Different time series signals can be used for studying the bed hydrodynamics such as pressure fluctuations [3,5,6], bed vibration [7–9], acoustic emissions [10–12] and local porosity [13]. However, pressure fluctuation measurements have some advantages that make them suitable for many practical applications. These advantages are ease of measurement and inclusion of the effect of various dynamic phenomena, such as bubble hydrodynamics, occurring in the bed [3,14].

The hydrodynamics of a fluidized bed are non-linear, and could be even considered chaotic, although the latter is being debated [15]. A way to describe the state of such a system is to project the variables governing the system into its multi-dimensional state space [14]. Recently, a new technique based on the nonlinearity of the dynamics, called recurrence quantification analysis RQA), has been developed [16]. The concept of the RQA, which relies on the presence of recurring/deterministic structures underlying the data, is a basic property of dynamical systems, which can be exploited to describe the behavior of the system in the phase space. Tahmasebpour et al. [17,18]) and Babaei et al. [19] demonstrated that RQA is a powerful tool to study fluidization hydrodynamics.

In the present study, nonlinear time series analysis technique based on RQA is explored to characterize the hydrodynamics of gas-solid fluidized beds, focusing on improving the scale-up procedure. It will be shown that how nonlinear RQA method can help to improve the Glicksman's non-dimensional scaling method [20] by identifying the most relevant dimensionless group as dictated by the RQA. The Shannon entropy, one of the quantitative concepts of the RQA method, is introduced to quantify the fluidized bed hydrodynamics representatively, based on measured pressure fluctuation data. The entropy is related to superficial gas velocity, size of particles, settled bed height and bed diameter. Then, this modeled entropy will be used to establish hydrodynamic similarities between two fluidized beds of diameters 9 and 15 cm ID.

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Nomenclature

a_j	approximate sub-signal
d	dimension of the system
d_s	particle size, μm
D	bed diameter, m
D_j	detail sub-signal
E_j^a	energy of approximation sub-signal at level j, Pa^2
E_j^D	energy of detail sub-signal at level j, Pa^2
ENT	entropy, bits/cycle
f	frequency, Hz
f_s	sampling frequency, Hz
G_s	solids circulation flux, kg/s.m^2
i	counter
j	complex number
j	wavelet decomposed information level
k	time lag coefficient
l	length of a diagonal line
l_{min}	predefined minimal length of diagonal lines
L	settled bed height, m
N	length of the time series
$p(l)$	number of diagonal lines with length of l
$R_{i,j}$	recurrence plot matrix
T	time, s
U_0	superficial gas velocity, m/s
U_{mf}	minimum fluidization velocity, m/s
$x(i)$	pressure time series, Pa
x_i	i-th point of space state trajectory
x_j	j-th point of space state trajectory
Greek letters	
ε	threshold radius
ψ	mother wavelet function
Θ	Heaviside function
ρ_s	particle density, kg/m^3
ρ_f	gas density, kg/m^3
φ	particle sphericity

2. Experiments

Experiments were carried out in 5 different gas–solid fluidized beds in the University of Tehran and Delft University of Technology. Experimental conditions are summarized in Table 1. Air at room temperature was supplied to the bed through a distributor and its flow rate was controlled by a mass flow controller. A cyclone, placed at the column exit, would return the entrained solids back to the bed. Various initial aspect ratios of solids (L/D = 1, 1.5 and 2) were used in experiments and the superficial gas velocity was varied in the range of 0.1–1.7 m/s. Sand particles (Geldart B) with a Sauter mean diameter of 150, 300, 400 and 600 μm and a particle density of 2700 kg/m^3 were used in the experiments.

Measured pressure signals were band-pass filtered at lower cut-off frequency and upper cut-off Nyquist frequency. The filtered signals were then amplified and sent to a data acquisition board system. Johnsson et al. [3] and van der Stappen et al. [21] recommended that the sampling frequency within the range of 50–100 times the average cycle frequency (typically between 100 and 600 Hz) is required for nonlinear evaluation of pressure fluctuations in bubbling fluidized beds. Selected sampling frequencies, lower cut-off and upper cut-off Nyquist frequencies and number of data points collected in each fluidized bed are shown in Table 1.

3. Method of analysis

Methods of data analysis used in this work are briefly described below.

3.1. Recurrence plot

The recurrence plot (RP) is a graphical explanation of the dynamics of a system [22]. A RP provides a qualitative picture of the correlations between the states of a time series over all available time-scales. It is a 2-dimensional plot which is mathematically expressed as:

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

where N is the number of considered states, $x_i, x_j \in R^d$ represent the i-th and j-th points of the d-dimensional state space trajectory, $\|\ \|$ represent the norm, ε is a threshold distance and Θ is the Heaviside function. The RP is obtained by plotting the recurrence matrix, Eq. (1); if $R_{i,j} = 1$ it is considered as a recurrence point and appears as a black dot at the coordinate (i, j), if $R_{i,j} = 0$ it is shown as a white dot. The RP can be constructed without embedding [23]. Therefore, in the present work, the embedding dimension was considered to be 1.

3.2. Recurrence quantification analysis

The RQA is developed for quantifying different graphical structures of RPs. Recurrence parameters describe distribution of various structures in the RP, including single dots, diagonal lines and vertical or horizontal) lines [16]. Entropy (ENT) in the RQA is the Shannon information entropy of the probability distribution of the diagonal line lengths l:

$$ENT = -\sum_{l_{\min}}^{N} p(l)\log_2 p(l) \tag{2}$$

The probability distribution of the diagonal line lengths $p(l)$ is defined as:

$$p(l) = P(l)/N_l \tag{3}$$

where $P(l)$ is the frequency distribution of the lengths l of the diagonal line in the RP and N_l is the number of diagonal lines.

Table 1
Experimental conditions.

Bed	Diameter (cm)	University	Particle size (μm)	Density (kg m^{-3})	Sampling frequency (Hz)	Lower cut-off frequency (Hz)	Upper cut-off frequency (Hz)	Data points
Bed 5	5	Tehran	150–300–600	2700	400	0.1	200	1,200,000
Bed 9	9	Tehran	150–300–600	2700	400	0.1	200	1,200,000
Bed 15	15	Tehran	150–300–600	2700	400	0.1	200	1,200,000
Bed 40	40	Delft	400	2700	80	Off	40	262,144
Bed 80	80	Delft	400	2700	200	Off	60	720,896