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Characterization of hydrodynamics of bubble columns by recurrence quantification analysis

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ABSTRACT

Bubble column reactors are nonlinear and chaotic systems and characterizing their hydrodynamics by linear methods does not offer appropriate information. Experiments were carried out in bubble column containing non-Newtonian shear thinning fluids with different viscosities. Three hydrodynamic structures (i.e., micro-scale, meso-scale and macro-scale) in bubble columns were detected. Frequency ranges corresponding to each structure was determined to be 0–6.25 Hz for macro-scale, 6.25–50 Hz for meso-scale and 50–200 Hz for micro-scale. Effect of superficial gas velocity on size of bubbles was invetigated by analysis of pressure fluctuations using Recurrence Quantification Analysis (RQA). The RQA was used to determine transition velocities in the bubble column. The transition velocity from homogeneous to heterogeneous was in the range of 0.05–0.06 m/s in the low viscous solution and transition velocity from heterogeneous to slug flow in the range of 0.02–0.03 m/s for the high viscous non-Newtonian solution.

1. Introduction

Multiphase contactors, such as bubble columns, fluidized beds and spouted beds are applicable in chemical, biochemical and petrochemical reactors. High mass and heat transfer rates, low operating cost, low maintenance demand and simplicity of design have made these contactors attractive from industrial point of view [1–4]. Gas-liquid contactors can be classified into three types based on flow of phases: co-current, counter-current and cross-current. Counter-current gas-liquid contactors have more applications compared to co-current contactors. Nevertheless, co-current contactors, have received more attention in recent years due to their inherent advantages such as simplicity, lower cost of operation, higher interfacial area, low pressure drop, continuous operation over a wide range of flow rates and fine dispersion and good mixing of phases [5]. The gas hold-up in counter-current contactors is higher compared to co-current [6]. A bubble column consists of a distributor at the bottom of a cylindrical vessel in which the gas is injected into the liquid or slug phase. Due to their broad application in various industries, studying the hydrodynamics of bubble column is vital. For better understanding the phenomena such as heat transfer, mass transfer and mixing in bubble columns, it is necessary to identifying the hydrodynamic characteristics of bubble columns, i.e., bubbles formation and the resulting circulation patterns [7]. Bubbles dynamics in a bubble column is a complex phenomenon. Therefore, it is important to characterize the behavior of bubbles [3,8]. Design and scaling up of bubble columns requires ample knowledge of their hydrodynamics due to the complexity of multiphase flows. Successful examples are bubble column fermenters which have been scaled up for few decades with typically only a ~10% or less loss of yield [9,10].

Various methods have been used for characterization of the hydrodynamics of bubble columns. Pressure signals of the bed have been proved to reflect the behavior of the bubbles. Consequently, analysis of pressure fluctuations is a usual method for investigation of bubbling systems [10]. This method is simple, inexpensive, non-intrusive and expandable to various experimental situations [11]. The sources of pressure fluctuations in a bubble column are related to interaction of bubbles such as formation, coalescence and motion along the column [12]. Gourich et al. [13] demonstrated that standard deviation of pressure fluctuations is constant at low gas velocities, which can be attributed to existence of the homogeneous regime, and increases at high velocities. They concluded that this change in the slope indicates the transition from homogeneous to heterogeneous regime. Vial et al. [14] carried out similar experiments in both bubble column and airlift reactors with uniform and non-uniform gas distribution. They found that the curve of standard deviation of pressure fluctuations against superficial gas velocity (u_{gs}) consists of three regions which correspond to the three flow regimes in the system. Yang et al. [15] reflected the regime transition from homogeneous to heterogeneous flow regime in a conceptual model calculation through the changes on the gas holdup vs. superficial gas velocity. They showed that this

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Nomenclature

a_j	approximation sub-signal
D	dimension of system
D_j	detail sub-signal
f	frequency (Hz)
f_s	sampling frequency (Hz)
i	counter
j	imaginary unit of the complex number
J	wavelet decomposed information level
k	level number
K	consistency index (Pa s^n)
l	length of a diagonal line
L	number of the time-series segments
M	number of points in space state
n	flow index
N	length of the time series
N_L	length of segments
p	probability function
$P(l)$	number of diagonal lines with length of l
$P(v)$	number of vertical lines with length of v
P_{xx}^n	power-spectrum estimate of each segment (Pa^2/Hz)
$P_{xx}(f)$	averaged power spectrum (Pa^2/Hz)
R_{ij}	recurrence plot matrix
S	Shannon entropy
t	time (s)
U	normalizing factor in Welch method
u	superficial gas velocity
w	window function
$x(i)$	pressure time series
x_i	ith point of space state trajectory
$X(f)$	estimated Fourier transform
$x(t)$	original signal

Greek letters

γ	shear rate (s^{-1})
ε	radius threshold
Θ	Heaviside function
μ_{app}	apparent viscosity (Pa s)
σ	surface tension
τ	time delay (s)
Ψ	mother wavelet function

model can describe the flow structures and momentum and energy exchange between phases. Guan et al. [16] carried out a study on bubble properties, measured by a dual-tip conductivity probe. They found a new method to establish the relationship between bubble size and chord length. Their results demonstrated that the flow development is more rapid in the churn turbulent flow regime compared to the homogenous flow regime. Letzel et al. [10] concluded that the transition zone cannot be distinguished correctly by this method. Vial et al. [14] analyzed pressure fluctuations of a bubble column in the frequency domain and extracted characteristic frequencies of the flow from the power spectral density function (PSDF). Frequency domain analyses of dynamical variables of the bubble column is not capable of determining the whole complexity of the bed. Moreover, the PSDF does not release all required information and is not an appropriate method for detecting regime transition [13,17]. Consequently, investigating the nonlinear behavior of bubble column still is a relatively new subject.

Studying the hydrodynamics of bubble columns is challenging due to strong interactions between bubbles and liquid [18]. The chaotic behavior of a system has been proved by analysis of pressure fluctuations in bubble columns [19]. All nonlinear methods for analysis of time-series data are based on transforming a variable of the system into its multi-dimensional state space. The main drawbacks of these methods are long-term data requirement, time-consuming calculations and uncertainty in determination of embedding parameters [20]. Recently, several researchers have utilized the Recurrence Plot (RP) to analyze the nonlinear time series [21]. Gao et al. [22] utilized RP for investigation of flow pattern in a bubble column. They showed that randomness of bubble flow can be reflected in RP structures. They detected the slug flow regime by RPs at high superficial gas velocity due to the periodic behavior of system in this flow regime. Goa et al. [23] also determined structures of slug and churn flow regime in RPs. Tahmasebpour et al. [24] investigated various hydrodynamic structures and determined their frequency ranges in a fluidized bed by Recurrence Quantification Analysis (RQA) of pressure fluctuations. Babaei et al. [25] used this technique and discussed the effect of superficial gas velocity on the hydrodynamic structures in a fluidized bed and showed that finer structures become dominant by increasing the velocity. Tahmasebpour et al. [26] also discussed the effect of particles size and bed diameter on the hydrodynamics by RQA. They showed that frequency range of each structure is not sensitive to the scale of the system. Sedighikamal and Zarghami [27] characterized the hydrodynamics of bubble and regime transition through RPs. Savari et al. [21] studied the behavior of spouted bed by analysis of pressure fluctuation signals and analytic emissions signals using RQA. Their RQA results showed that injecting water into the bed leads to increasing maximum length of diagonal lines and therefore system status become more deterministic.

Considering effectiveness of RP and RQA in characterizing the hydrodynamics of fluidized beds, the RQA, as a powerful tool for characterizing nonlinear systems, was utilized for investigating the hydrodynamics of bubble columns, in the present work. This technique has not been previously used for investigating the hydrodynamics of bubble column and is able to reveal the bubble dynamics in various operating conditions. In fact, the frequency ranges of macro, meso and micro structures as well as transition of the flow regime from homogeneous to heterogeneous to slugging can be detected with this technique.

2. Experiments

Experiments were carried out in the batch mode, in a Plexiglas column with 1700 mm height and 90 mm diameter, shown in Fig. 1. A perforated plate distributor with 151 holes of 0.5 mm diameter was used for uniform distribution of air. A mass flow rate controller (Alicat – 50 SLPM) was used for adjusting the gas flow rate. Before the tests, the column was filled with tap water up to the height of 1350 mm (aspect ratio of 15). The aspect ratio is an important parameter which affects the holdup and transitional velocity in bubble columns. However, there is a critical value for the aspect ratio at which the homogeneous regime can become unstable by increasing the superficial gas velocity. This value ranges between 5 and 10, depending on the bubble column operating conditions [28]. Since the aspect ratio was 15 in the experiments of this work, heterogeneous regime can be formed by increasing the superficial gas velocity, as was also recognized by visual observation during the experiments.

By dissolving a small amount of Carboxy Methyl Cellulose (CMC) powder in water, different concentrations of a non-Newtonian solution were prepared (0.05% CMC corresponding to low viscosity of 1.42 cP and 0.6% CMC corresponding to high viscosity of 21 cP) [29]. For stability and reaching complete homogeneity of the polymer, the solution was kept at low temperature (between 4 and 8 °C) for at least 8 hours. Physical properties of these solutions are given in Table 1. A pressure probe (model SEN-3248 (B075), accuracy class of 0.5%, Kobold Co.) was used to measure the pressure fluctuations at the wall of the bed. This probe