FLOW REGIME TRANSITION IN BUBBLE COLUMNS VIA NUCLEAR GAUGE DENSITOMETRY: APPLICATION OF NON-LINEAR CHAOS ANALYSIS

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Summary

Bubble column performance can be changed significantly as a result of flow regime change. Since reactor volume productivity, mass and heat transfer as well as mixing are affected by the prevailing flow regime, it is very important to know how to identify it. In this work, the flow regime identification was performed using non-linear chaos analysis based on the Kolmogorov entropy algorithm applied to nuclear gauge densitometry data. In addition, the average cycle time was used for the validation of the results. Three transition velocities (0.035, 0.05 and 0.07 m/s) were identified which delineated the boundaries of the four main hydrodynamic regimes.

Keywords

Multiphase reactors, Dynamics and control of chemical systems, Process intensification, Multiscale analysis.

Introduction

Gas-liquid bubble columns (BCs) are frequently used in chemical, petroleum, biochemical and waste water treatment industries due to their simple construction, easy temperature control and good heat/mass transfer characteristics. A good knowledge of the BC hydrodynamics and flow regime transitions is required for reliable and energy efficient design, operation, control and scale-up purposes.

Three major flow regimes are formed in BCs: homogeneous (bubbly flow), transition and heterogeneous (churn-turbulent flow). In addition, some authors[1-3] have provided evidence for the existence of first and second transition regimes. Therefore, three transitional gas velocities U_{trans} should be distinguishable. In these different flow regimes, the interaction of the dispersed gas phase with the continuous liquid phase varies considerably[4]. Nedeltchev and coworkers[5-8] performed systematic identification of the boundaries of each flow regime based on the analysis of both Computer-Automated Radioactive Particle Tracking (CARPT) and Computed Tomography (CT) data as well as differential pressure time series. Using CT data measured in air-therminol LT system (gas sparger: $163 \times Ø\ 1.32\times10^{-3}$ m), Nedeltchev et al.[6] found that $U_{trans}\approx0.02$, 0.08 and 0.1 m/s, respectively. In the case of differential pressure fluctuation data measured in 1-butanol and nitrogen (gas sparger: $19 \times Ø\ 1\times10^{-3}$ m), Nedeltchev et al.[8] reported that $U_{trans}\approx0.02$, 0.042 and 0.073 m/s. For gasoline-nitrogen system, $U_{trans}\approx0.021$, 0.053 and 0.078 m/s, respectively.

The bubbly flow regime is characterized by gentle agitation of the gas-liquid dispersion by means of small, uniform bubbles which do not tend to coalesce. The bubble size distribution is very narrow and it is mainly influenced by the gas sparger. A relatively uniform gas holdup profile and less steeper liquid velocity profile are observed.

The transition flow regime is characterized by the development of local liquid circulation patterns, large flow macrostructures (large eddies) and widened bubble size distribution. The latter is due to the onset of bubble coalescence. The stability of the transition regime depends largely on the uniformity and the quality of the aeration.

In the churn-turbulent regime larger bubbles begin to form and their wakes cause gross circulation patterns in the bubble bed. This flow regime is characterized by wide bubble size distribution, coherent structures and by the existence of steeper radial gas holdup profile which causes liquid circulation. Hence, simultaneous coalescence and break-up occur. In this regime, the gas sparger has little effect and the mixing is vigorous. Frequently, spiral and chaotic liquid flow pattern is observed in the fully developed churn-turbulent regime.

Shaikh[9] in his thesis and Shaikh and Al-Dahhan[10] demonstrated the ability of Nuclear Gauge Densitometry (NGD), which is used commercially for liquid/slurry measurement and control, to identify the boundaries of the prevailing hydrodynamic flow regime in BCs. The concept was evaluated based on the studies performed in air-water

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system in 0.1 m diameter column and the comparison with traditional flow regime identification methods such as the change in the slope of overall gas holdup with superficial gas velocity and drift flux plot.

Accordingly, the main objective of this work is to apply the nonlinear chaos theory based on Kolmogorov entropy to NGD data obtained by Shaikh et al.[9,10] to evaluate its capability to identify flow regime transition.

Experimental

Nonintrusive Nuclear Gauge Densitometry (NGD) measurements were performed in a plexi-glass BC (0.1 m in ID, 1.2 m in height) operated with air-water system at ambient conditions. The superficial gas velocities u_G were varied from 0.01 m/s up to 0.12 m/s with a step of 0.05 m/s around the first transition velocity. The BC was equipped with gas sparger consisting of 64 holes of 1.32×10^{-3} m in ID with an open area of 1.09 %. During the experiments, a focused beam of radiation was transmitted from the source through the column and process material to the scintillation detector. The photon counts history was collected at a sampling frequency of 50 Hz for acquisition time period of 5 minutes. The details of the experimental set up and technique can be found somewhere else[9,10].

The photon counts history (of length 10,000) was treated by means of the Kolmogorov entropy (KE) algorithm[11] which is a part of the nonlinear chaos theory. The number of vector elements (embedding dimension) was set equal to 50, the delay time was chosen to be unity and the cut-off length was fixed at three times the average absolute deviation (which is a robust estimator of the data's width around the average value).

Results and discussion

Fig. 1 shows that at u_G=0.035 m/s the KE profile exhibits a local peak (instability point) which means that the bubbly flow regime transforms itself into first transition flow regime. This KE maximum corresponds to the onset of formation of large (coalesced) bubbles. The second transition velocity occurs at u_G=0.05 m/s where second local KE peak appears marking the beginning of the second transition regime. The onset of the churn-turbulent regime occurs at u_G=0.07 m/s (third KE peak). It is worth noting that at each particular u_G value, three measurements were performed and then the KE value was averaged (mean relative error ≤ 5 %). These three transition velocities can be theoretically predicted considering the fact[12] that at Tadaki number Ta ($=Re_bMo^{0.23}$) equal to 6 the shape of the bubbles changes from oblate ellipsoidals to prolate ellipsoidals, whereas at Ta=16.5 mushroom-like bubbles begin to form. The formula of Reilly and coworkers[13] for the critical gas holdup should be used for predicting the first two transitional gas velocities.

Fig. 1 exhibits also the successful modeling of the KE values in bubbly and churn-turbulent flow regimes. In both cases, the KE was correlated to bubble frequency and bubble impact. It was taken into account that the bubble impact plays more important role in the heterogeneous regimes. In the bubbly flow regime the mean bubble size was estimated by one of the correlations summarized in Miller[14], whereas in the churn-turbulent regime the large bubble size was calculated based on the simplified bubble coalescence model[15]. Fig. 1 shows reasonable agreement between experimental and predicted KEs in both bubbly and churn-turbulent regimes.

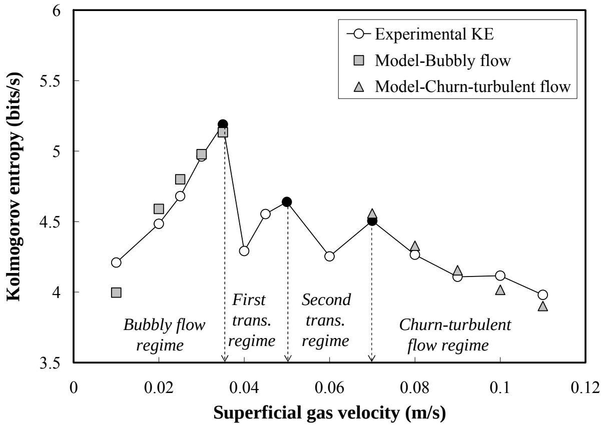

Fig. 1. Identification of transition velocities in a bubble column on the basis of the KE values as a function of u_G.

Fig. 2 illustrates that the values of average cycle time T_c (the average time that is needed to complete a full cycle after the first passage through the average of the signal)[16] as a function of superficial gas velocity can distinguish clearly two transitional velocities. The first one occurs at u_G=0.035 m/s where the rate of T_c increase suddenly changes. The second U_{trans} occurs at u_G=0.07 m/s where the rate of T_c increase changes again. These transition velocities coincide with the first and third ones in Fig. 1, however the second transition velocity (between both transition regimes) cannot be predicted based on the T_c.

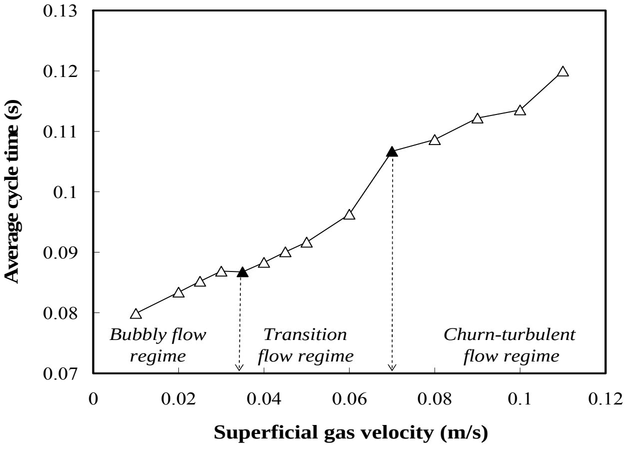

Fig. 2. Application of average cycle time T_c for identifying the main transition velocities in a bubble column.

The presented results show that the KE algorithm and the average cycle time can be applied successfully to NGD data for the sake of identification of the transition velocities between the main hydrodynamic regimes.

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