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New methods for flow regime identification in bubble columns and fluidized beds ☆

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ABSTRACT

New methods for flow regime identification were developed and applied to photon count time series measured in a bubble column (0.162 m in ID) and fluidized bed (0.438 m in ID). The signals in the bubble column (operated with an air-therminol system) were measured by means of Computed Tomography (CT), whereas the data in the fluidized bed (operated with an air-polyethylene system) were recorded by means of Nuclear Gauge Densitometry (NGD). The hidden information in the time series was extracted by means of two new parameters: entropy (bit/s) and information entropy (bit). Both of them were calculated on the basis of multiple reconstructions of the time series. In the case of the bubble column, the well-pronounced local minima were used for identification of three transition velocities (0.04, 0.08 and 0.13 m/s). They distinguished the boundaries of the bubbly flow, transition and churn-turbulent flow regimes. In the case of the fluidized bed, the minimum fluidization velocity (0.086 m/s) and minimum bubbling velocity (0.12 m/s) were also identified on the basis of the well-pronounced local minima in the profiles of the new parameters. They distinguished the boundaries of both the transition and bubbling fluidization regimes.

1. Introduction

The performance of multiphase reactors is affected by the flow regime and the quality of the gas distribution (Briens et al., 1997). The prediction of regime transition velocities U_{trans} in multiphase reactors (bubble columns, fluidized beds, etc.) is very important for their design and scale-up as well as effective operation. The rates of heat and mass transfer as well as mixing and conversion are quite different in the main hydrodynamic regimes. It is essential to know the range of physical properties and operating parameters over which the main flow regimes prevail. For instance, Ajbar et al. (2009) argue that it is often desirable to operate the bubble columns in the homogeneous regime and thus it is essential to identify precisely its boundaries. Chen et al. (1994) studied carefully the flow structure in a three-dimensional bubble column and three-phase fluidized bed. The authors documented the existence of various flow regimes and sub-regimes. In addition to their study, Olmos et al. (2003a) provided an evidence for the existence of both first and second transition sub-regimes.

The main transition velocities are associated with flow instabilities. Jackson (1963) was one of the first researchers who studied the stability of the state of uniform fluidization. Batchelor (1988) has developed a new theory of the instability of a uniform fluidized bed. Shnip et al. (1992) established criteria for the transition from the homogeneous to the heterogeneous regime in two-dimensional bubble column reactors. León-Becerril and Liné (2001), Joshi et al. (2001) and Bhole and Joshi (2005) studied also the hydrodynamic stability of multiphase reactors. Monahan and Fox (2007) applied the linear stability analysis to air-water bubble columns. The theory of linear stability was used by Bhole and Joshi (2005) for identifying the transition velocity. In addition, Computational Fluid Dynamics (CFD) simulations (Olmos et al., 2003b; Monahan et al., 2005; Simmonet et al., 2008) have been also performed.

The survey of the vast literature devoted to flow regime identification in multiphase reactors reveals still serious gaps which encourage further research in this area. There is at present no reliable method for identification of the boundaries of the main flow regimes in industrial multiphase reactors. Even well-designed reactors encounter gas maldistribution problems as the distributor becomes plugged.

The topic of flow regime identification has been actively investigated in the past 50 years. Anderson and Quinn (1970) studied the presence of trace contaminants on flow regime

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transitions. An interesting identification of the onset of the transition flow regime in bubble columns was presented by Deckwer et al. (1973). The authors reported that in the U_G range from 0.0024 to 0.062 m/s, zones of different liquid mixing exist. The backmixing in the upper zone of the column is about twice that in the lower zone of the column. At U_G=0.062 m/s the splitting into two mixing zones disappears again and it can be observed a single axial dispersion coefficient for the whole bubble bed. The point of separation lies approximately in the middle of the bubble bed.

The topic of flow regime identification is still very interesting for the researchers. For instance, the effect of bubble column dimensions on flow regime transition has been researched by Ruzicka et al. (2001a). Ruzicka et al. (2003, 2008) investigated the effect of viscosity on homogeneous-heterogeneous flow regime transition and the effect of surfactant on homogeneous regime stability in a bubble column. Mota et al. (2011) studied the effect of spent grains on the flow regime transition in a bubble column. Mena et al. (2005) studied the effect of solids on the homogeneous-heterogeneous transition in bubble columns. Ribeiro and Mewes (2007) investigated the influence of electrolytes on regime transition in bubble columns. Ruthiya et al. (2005) detected the flow regime transitions in slurry bubble columns based on pressure fluctuations. In the past five years, in the field of bubble columns many new papers (Hur et al., 2013; Mota et al., 2011; Nedeltchev et al., 2011; Nedeltchev and Shaikh, 2013; Shaikh and Al-Dahhan, 2013; Şal et al., 2013; Shiea et al., 2013) have been published.

Numerous methods for flow regime identification in multiphase reactors have been proposed in the literature. An overview of the methods applied to different signals measured in bubble columns has been presented by Shaikh and Al-Dahhan (2007) and Nedeltchev and Shaikh (2013). Most of the methods are standard (for instance, statistical analysis or drift flux analysis). Several modern methods (fractal analysis, spectral analysis, nonlinear chaos analysis and wavelet analysis) have been used in bubble columns. Briens and Ellis (2005) applied simultaneously most of these methods to three-phase fluidized bed systems. Fraguío et al. (2007) classified the flow regimes in three-phase fluidized beds on the basis of radioactive particle tracking experiments.

Statistical methods have been used by Vial et al. (2000) and Gourich et al. (2006). Fractal analysis (Fan et al., 1993) and wavelet analysis (Ellis et al., 2003; Lu and Li, 1999) have been proposed to describe the dynamic behavior of two-phase flow successfully. Drahoš et al. (1992) used Hurst's analysis to discriminate between flow regimes in a gas–liquid bubble column. Briens et al. (1997) applied also Hurst's analysis to detect the minimum fluidization velocity and gas maldistribution in fluidized beds. Spectral analysis (Ajbar et al., 2009) has been also used for flow regime identification. Bakshi et al. (1995) used multi-resolution methods for analysis of flow in bubble columns. Briongos et al. (2006) applied phase space structure and multiresolution analysis to study the gas–solid fluidized bed hydrodynamics. Decoupling methods have been also applied to pressure fluctuations in gas-fluidized beds (Zhang et al., 2010).

The nonlinear chaos analysis has been applied extensively for flow regime identification in gas–solid flows (Daw et al., 1990), fluidized beds (Bai et al., 1997; Ellis et al., 2003; Marzocchella et al., 1997; Van den Bleek and Schouten, 1993) and bubble columns (Ajbar et al., 2009; Cassanello et al., 2001; Kikuchi et al., 1997; Letzel et al., 1997; Lin et al., 2001; Nedeltchev et al., 2003, 2006). It is worth noting that Van der Schaaf et al. (2004) have shown that a similarity between chaos analysis and frequency analysis exists. In other words, a direct relationship exists between Kolmogorov entropy and power spectral density of pressure drop fluctuations in a fluidized bed.

Lin et al. (2001) extracted both a metric entropy and mutual information from differential pressure fluctuations measured in a bubble column in order to identify the main flow regimes. However, the flow regime identification based on these parameters was not very clear.

Another interesting new method for flow regime identification is based on the Shannon entropy (Zhong et al., 2009). The larger Shannon entropy corresponds to higher disorder in the system. This implies more complex and chaotic nature resulting in turbulent motion of the gas or particles, gas–solid or gas–liquid intensive interactions, flow instability, etc. The Shannon entropy is a measure of the degree of indeterminacy in a certain system. Based on the Shannon entropy, Zhong et al. (2009) identified the boundaries of five different flow patterns in a pressurized spout-fluid bed. Kang et al. (1999) used the Shannon entropy of pressure fluctuations to detect the flow pattern transitions in three-phase fluidized beds.

In the field of gas–solid fluidized beds, a promising method was developed by Gómez-Hernández et al. (2014). The authors performed a wide band energy analysis of fluidized bed pressure fluctuation signals using a new frequency division method. Recent methods on flow regime identification in gas–solid fluidized beds have been published by Tamadondar et al. (2012), Saayman et al. (2013), Jaiboon et al. (2013), Llop et al. (2015) and Zhu et al. (2013). The first research team used particle trajectories to determine the boundaries of the fluidization regimes. Saayman et al. (2013) used a fast X-ray tomography for the quantification of the main fluidization regimes. Makkawi and Wright (2002) characterized the fluidization regimes by means of electrical capacitance tomography. Kuwagi et al. (2014) proposed a three-dimensional flow regime map for fluidization analyses. Babaei et al. (2012) and Llop et al. (2015) characterized the main flow regimes in fluidized beds on the basis of recurrence plots. Babaei et al. (2013) monitored the fluidized bed hydrodynamics using recurrence quantification analysis. Chalermsinsuwan et al. (2014a,b) provided a revised fluidization regime characterization in high solid particle concentration circulating fluidized bed reactor. Zhu et al. (2013) identified the flow structures and regime transitions in gas–solid fluidized beds through a new moment analysis method called moment consistency data processing method. De Martín et al. (2011) detected the regime transitions in gas–solid fluidized beds based on low frequency accelerometry signals. Briongos and Soler (2004) used the free bed surface fluctuations in a fluidized bed for flow regime identification. Abbasi et al. (2010) used vibration signature analysis for nonintrusive characterization of fluidized bed hydrodynamics.

1.1. *Importance of pressure fluctuations for flow regime identification*

In the past 20 years, the nonlinear analysis of pressure fluctuations has been used by different research groups (Bai et al., 1997; Johnsson et al., 2000; Llauró and Llop, 2006; Llop et al., 2012; Zijerveld et al., 1998) for both characterization and classification of fluidization regimes. Tahmasebpour et al. (2013a,b) studied the transition velocity from bubbling to turbulent fluidization and characterized the various structures in fluidized beds based on recurrence quantification analysis. Neogi et al. (1988), Bai et al. (1996, 1999) and Zhao and Yang (2003) used also pressure fluctuations for characterization of fluidization regimes. Sedighikamal and Zarghami (2013) applied recurrence rate analysis to pressure fluctuations to characterize the bubbling fluidization regime. Ge and Li (2002) proposed a new approach for physical mapping of fluidization regimes.

Good brief overview of the different measurement signals used for flow regime identification in bubble columns is available in Ajbar et al. (2009). Pressure fluctuations have been always used to provide qualitative information on the dynamics of multiphase reactors. Many researchers (Bai et al., 1997; Barghi et al., 2004;