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Flow regime identification in a three-phase bubble column based on statistical, Hurst, Hilbert–Huang transform and Shannon entropy analysis

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HIGHLIGHTS

- Statistical, Hurst, Hilbert–Huang transform and Shannon entropy analysis are used.
- Flow regime transitions in a three-phase bubble column are detected.
- EMD energy entropy is effective for flow regime identification.
- Shannon entropy shows dynamic behavior characteristics of three-phase bubble columns.
- The transition gas velocities show good agreement with the experimental results.

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ABSTRACT

Flow regime transitions in a gas–liquid–solid three-phase bubble column were investigated based on pressure time series. The statistical, Hurst, Hilbert–Huang transform and Shannon entropy analysis methods were applied to differential pressure fluctuation data measured in a two-dimensional (2-D) bubble column measuring 0.1 m in length and 0.01 m in width equipped with a sintered plate distributor (average diameter of holes was 50 μm). Air was used as the gas phase and tap water as the liquid phase. Glass beads measuring 150 μm in size with a particle density of 2500 kg/m^3 constituted the solid phase. Based on sudden changes in both the EMD energy entropy from Hilbert–Huang transform and the Shannon entropy values, two flow regime transition gas velocities were successfully identified: the homogeneous regime shifted to the transition regime at a superficial gas velocity of 0.069 m/s; and the transition regime shifted to the heterogeneous regime at a superficial gas velocity of 0.156–0.178 m/s. The transition gas velocities showed good agreement with the experimental results. The EMD energy entropy and Shannon entropy analysis methods can reveal the complex hydrodynamics underlying gas–liquid–solid flow and are confirmed to be reliable and efficient as non-invasive methods for detecting flow regime transitions in three-phase bubble column systems.

1. Introduction

Three-phase bubble columns are gas–liquid–solid fluidization systems in which a gas is dispersed through a gas distributor and passes through solid–liquid phases of the system bed in the form of bubbles. When fine solids are employed, a slurry phase is formed, and the column is referred to as a slurry bubble column (Jhawar and Prakash, 2012); When the particle size is larger than 100 μm (Jhawar and Prakash, 2012)—particles as large as 1–3 mm are used in some biological reactors (Fan, 1989; Rani et al., 2004) and in some experimental systems (Gan, 2013)—the column can be universally defined as a three-phase bubble column. Three-phase bubble columns have been widely applied in various chemical, petrochemical, biochemical and pharmaceutical processes, such as coal liquefaction, Fischer–Tropsch synthesis, hydrotreating of heavy petroleum residues, methanol synthesis, flue gas desulfurization, aerobic treatment of biological waste water, fermentation and the electrode in three-phase fluidized bed (Fan, 1989; Gandhi et al., 1999; Li, 2008; Mota et al., 2011). The intrinsic advantages of three-phase bubble columns are simple construction, excellent heat and mass transfer rates and ease of temperature control, no moving parts and low maintenance costs (Ashfaq and Muthanna, 2007; Barghi et al., 2004; Jhawar and Prakash, 2012). Much research must still be performed to address the complex hydrodynamics of the gas–liquid–solid system. The factors

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contributing to this complex behavior mainly include the effects of particle properties such as particle size, particle concentration, particle density and particle shape on gas–liquid flow, complex bubble–bubble, gas–liquid and particle–liquid interactions, bubble coalescence and break-up processes, especially when particles exist in systems, and the physico-chemical properties of the gas, liquid and solid phases.

Understanding the flow regimes in three-phase bubble column systems is very important to reactor design and scale-up (Nedeltchev et al., 2006). The study of flow regimes can help resolve the complex hydrodynamics of three-phase bubble columns and optimize the operating conditions of system beds. Different flow regimes affect reactor performance in many respects, such as pressure fluctuation, mass transfer, heat transfer, momentum loss, mixing and reactor volume productivity (Nedeltchev et al., 2006). When flow structures change, the performance of a three-phase bubble column changes. Homogeneous regime (dispersed bubble flow), transition regime and heterogeneous regime (coalesced bubble flow) are three types of flow patterns often observed in a bubble column (Ruthiya et al., 2005; Nedeltchev et al., 2006). The heterogeneous regime is required in most industrial reactors, whereas the homogeneous flow regime is desired in some bioreactors (Ribeiro, 2008). Hence, further information and insight regarding the study and identification of flow structures in a three-phase bubble column under different superficial gas velocities are valuable and important.

Many literature studies have investigated flow regime transitions in gas–liquid bubble columns (Ashfaq and Muthanna, 2007, 2013). The three main types of methods for identifying flow regime transitions (Ashfaq and Muthanna, 2007) are experimental methods, prediction methods based on mathematical models and computational fluid dynamics (CFD) methods. The experimental methods of flow regime identification involve visual observation; global hydrodynamic parameter evolution; temporal signatures of quantity for hydrodynamic measures and advanced measurement techniques. Pressure fluctuations analysis has been used to characterize fluidization regimes in many studies (Johnsson et al., 2000; van Ommen et al., 2011; Zhong et al., 2009). There are four categories of pressure fluctuation analysis: time domain analysis, frequency domain analysis, time–frequency domain analysis and state space analysis (Sasic et al., 2007). Time domain analysis involves the analysis of standard deviations and higher-order moments, e.g., skewness and kurtosis, the autocorrelation function, the cross-correlation function and Hurst analysis. Frequency domain analysis involves power spectrum analysis. Time–frequency domain analysis involves short-time Fourier transform, the wavelet transform and Hilbert–Huang transform analyses. State space analysis is used to determine non-linear characteristics and involves attractor reconstruction, e.g., Kolmogorov entropy and the correlation dimension, entropy analysis, e.g., Shannon entropy (Sasic et al., 2007; van Ommen et al., 2011).

Studies that have been performed on the flow regime identification of three-phase bubble columns are summarized in Table 1. Barghi et al. (2004) used gas holdup and pressure fluctuation analysis to identify flow regimes in a slurry bubble column. The researchers observed a free bubbling regime when the gas velocity was below 0.05 m/s and gross recirculation patterns when the gas velocity was above 0.125 m/s. The methods used for pressure fluctuation analysis fall under time domain analysis and can only reveal the linear characteristics of a system. Ruthiya et al. (2005) developed an unambiguous flow regime transition identification method based on the coherent standard deviation and the average frequency analysis of pressure fluctuations in slurry bubble columns. The authors noted that statistical analysis, fractal and chaos analysis, time–frequency analysis using wavelet transform, the autocorrelation function and average cycle frequency have been utilized to characterize flow regimes and transition points in bubble columns (Drahos et al., 1991, 1992; Letzel et al., 1997; Lin et al., 2001; Yong et al., 1996). The coherent standard deviation and the average frequency analysis used in these studies fall under frequency domain analysis, and Ruthiya et al. found these methods to be effective in characterizing flow regimes and pinpointing flow regime transitions. The researchers observed that the transition points from incoherent standard deviation analysis did not always correspond to the changes in the flow structures of the physical phenomena observed. Nedeltchev et al. (2006) studied a bubble column that can also be used as a slurry bubble column. Statistical and chaotic parameters were employed to analyze computed tomography data. Five flow regimes were identified: a dispersed bubble regime, first and second transition regimes, a coalesced bubble regime consisting of four regions (called 4-region flow) and a coalesced bubble regime consisting of three regions (called 3-region flow). All of the transition gas velocities at different operating conditions were determined. The average absolute deviation adopted in previous is a tool of time domain analysis, and use of the Kolmogorov entropy connotes state space analysis. Researchers have also found that non-linear chaos analysis can be successfully applied to computed tomography data for the identification of various flow regime boundaries. However, the selection of the transition points in Kolmogorov entropy —superficial gas velocity curves is optional due to the many points of rapid change observed in these curves. Hu et al. (2009) used the maximum Lyapunov exponent to study flow patterns in a slurry bubble column and observed that the exponent adopted different values for different flow patterns; however, the values of the transition gas velocities were not presented. Separating the three main flow regimes with two transition points remains a difficult task (Ruthiya et al., 2005). The aforementioned analysis methods generally focus on one or two analytical techniques and comparisons thereof are limited. Therefore, it is necessary to develop more efficient methods and carry out further studies on flow regime identification for three-phase bubble columns. In this study, the statistical, Hurst, Hilbert–Huang transform and Shannon entropy analysis methods were implemented and compared.

The Hilbert–Huang transform (HHT) was first developed by Huang et al. (1998, 1999) and has been applied, for example, in studies of the ocean, multiphase flow, machinery fault diagnosis, dynamic and earthquake motion signals (Zhang et al., 2003). The HHT can operate with time-adaptive decomposition, which distinguishes it from other time–frequency analysis methods.

Table 1
Previous studies on flow regime identification in a three-phase bubble column.

Reference	Parameter studied	Analysis method	Gas/liquid/solid properties	Column dimension/ operating parameters
Barghi et al. (2004)	Pressure fluctuations signals	Statistical and gas holdup analysis	Air/tap water/glass beads. $d_p=35\ \mu m$	$D=0.15$ m
Ruthiya et al. (2005)	Pressure fluctuations signals	The coherent standard deviation and the average frequency	Nitrogen gas/silica, carbon/demineralized water, $d_p=44\ \mu m$, 30 μm	2-D and 3-D bubble columns;
Nedeltchev et al. (2006)	Computed tomography data	Statistical and chaotic method, Kolmogorov entropy	Air/therminol LT	$D=0.162$ m $U_g=0.01$–0.2 m/s
Hu et al. (2009)	Pressure fluctuations signals	Chaotic analysis method, maximum Lyapunov exponent	Air/tap water/glass beads. $d_p=43\ \mu m$	$D=0.1$ m