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Flow regime transitions in a bubble column

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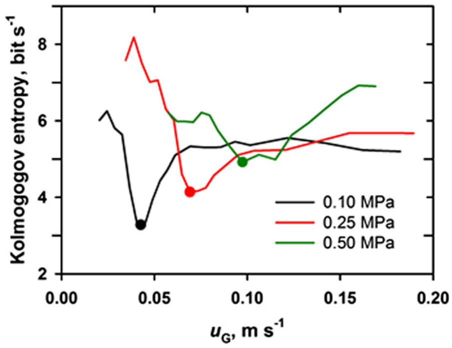
HIGHLIGHTS

- Flow transitions in a bubble column are identified based on the pressure fluctuation.
- Up to four flow regimes can be observed.
- Different analysis methods show systematic differences.
- The Kolmogorov entropy is most accurate in determining the main flow transition.

GRAPHICAL ABSTRACT



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ABSTRACT

In a 0.102 m ID bubble column, various techniques for flow regime identification based on pressure fluctuation measurement were applied: standard deviation, fractal analysis, Kolmogorov entropy K_E and power spectral density. The superficial gas velocity reached up to 0.2 m s^{-1} and the pressure was varied up to 2 MPa. Up to four flow regimes could be identified: intermittent, homogeneous, transition and heterogeneous flow. K_E shows a sharp minimum at the end of the homogeneous regime and start of the transition or heterogeneous regime, respectively. Overall, K_E is the most accurate method to determine this main transition. The fractal analysis shows a minimum at a clearly lower gas velocity. The standard deviation and the power spectral density are less accurate than K_E but more convenient since the value obtained in a single measurement could be compared to a threshold.

1. Introduction

Bubble column reactors are particularly effective in the homogeneous (bubbly) flow regime characterised by similarly small bubbles with low rise velocity. Coalescence to large bubbles at a critical superficial gas velocity, depending on gas and liquid properties but also the column geometry and distributor type, leads to heterogeneous (churn-turbulent) flow. Then fast rising large bubbles reduce the gas phase conversion and increase liquid mixing. Depending on the system and the observation method, a transition regime may be observed.

The identification of the prevailing flow regime in bubbles columns started with visual observation and gas hold-up analysis. Most of the authors in the literature agree with the subjectivity of the first method and the lack of accuracy of the second one. The use of the drift flux, calculated from the gas hold-up (Zuber and Findlay, 1965; Wallis, 1969), increases the sensitivity only marginally. This led to the development of many other methods such as the analysis of the pressure fluctuations, the analysis of the sound produced and sophisticated computational methods such as automated particle tracking or tomography.

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The measurement of pressure fluctuations, differential pressure or absolute (gauge) pressure, is experimentally simple and cheap. It can be applied at laboratory and industrial scale without influencing the flow in the reactor (Vial et al., 2000). The analysis methods can be classified into statistical (probability density function, standard deviation), spectral (power spectral density), fractal (fractal dimension, Hurst exponent) and chaos analyses (Lyapunov exponent, correlation dimension, Kolmogorov entropy). A detailed overview of previous studies based on analysis of the pressure fluctuations is given in Table 1.

The results reported in the literature show large discrepancies. It is mostly not clear whether these are systematic and characteristic for the analysis method or result from differences in the experimental conditions. Therefore, the various methods are compared in this study using the same pressure fluctuation data.

1.1. Statistical analysis

The statistical analyses are based on the evolution of statistical parameters as a function of the superficial gas velocity u_G. The Probability Density Function (PDF) has been used first (Tutu, 1982). It is just the probability of discrete pressure values in a dataset. A pronounced peak is characteristic of the homogeneous regime; the heterogeneous flow regime is characterised by a bimodal curve. Despite these differences, an accurate identification of the flow transition is not possible (Shaban and Tavoularis, 2014). This lack of accuracy of the PDF led to the investigation of its different moments.

The second moment of the PDF, the standard deviation σ, measures the dispersion of a set of N data values around its mean value $\overline{P}$:

$$\sigma = \sqrt{\frac{1}{N-1} \times \left(\sum_{i=1}^{N} (P_i - \overline{P})^2\right)} \quad (1)$$

The standard deviation shows very low values in the homogeneous regime and then increases with u_G. Vial et al. (2001) proposed the criterion $\sigma/\overline{P} = 1.5$ for the end of the homogeneous regime; unfortunately, the critical value depends strongly on the experimental conditions. Gourich et al. (2006) reported the successful use of σ for the identification of the flow regime boundary but there is no sharp transition (Letzel et al., 1997; Lin et al. 1999). Recently Nedeltchev and Shaikh (2013) used the average absolute deviation AAD as an alternative which gives the same trends. Still higher moments of the PDF, the skewness and the kurtosis, have also been tested (Table 1) but the results disagree considerably.

1.2. Fractal analysis

The fractal or stochastic analysis derives from the work of the British hydrologist Harold E. Hurst. The method consists in characterising a dataset by the comparison of the cumulated fluctuation (R) of the signal around its mean value to its dispersion (S) around this mean value, the rescaled range (R/S). Hurst further applied the analysis to shorter segments of the dataset, which he correlated to the time lag τ. between two events:

$$\left(\frac{R}{S}\right)_{\tau} = \tau^{H} \quad (2)$$

The method is explained in detail by Franca et al. (1991), Drahoš et al. (1992), Vial et al. (2000), and Li et al. (2013). The value of H is a real number in the interval [0,1]. $H > 0.5$ indicates a persistent process. Such processes have a "long-term memory" meaning that they tend to conserve their previous tendency, increasing or decreasing. $H < 0.5$ for an anti-persistent process and $H = 0.5$ for a random process.

The stochastic analysis allows the determination of slow and rapid stochastic phenomena that are cyclic, but not necessarily periodic (Gourich et al., 2006). Since the Hurst exponent is based on the self-similarity principle as the fractal theory, the method was renamed fractal analysis, deducting the fractal dimension d_F from the Hurst exponent H:

$$d_F = 2 - H \quad (3)$$

Vial et al. (2000) observed a pronounced persistent character in the homogeneous regime and anti-persistent character for the fully developed heterogeneous flow. No clear transition could be identified. Gourich et al. (2006) noticed a discrepancy between the results of Vial et al. (2000) and Drahoš et al. (1992); they suggested the transition to occur at a sudden increase of H. Recently, Li et al. (2013) reported a strong increase of H in the homogeneous regime and identified a maximum as the transition point which was not in agreement with the other methods they used.

Table 1
Overview of flow regime analyses using the pressure fluctuations.

Authors	Photography/ visual	Gas hold-up	Drift flux	Probability density	Standard deviation	Skewness/ kurtosis	Kolmogorov entropy	Lyapunov exponent	Correlation dimension	Fractal dim./ Hurst exp.	Power spectral density	Other methods
Li et al. (2013)	×				×	×				×		×
Nedeltchev and Shaikh (2013)							×					×
Zhang et al. (2010)									×			×
Zhang et al. (2009)											×	
Zhang and Li (2009)		×								×	×	
Hu et al. (2009)								×			×	
Nedeltchev et al. (2007)		×					×					
Gourich et al. (2006)		×	×		×				×	×	×	
Barghi et al. (2004)		×	×	×	×	×						
Vial et al. (2001)		×	×								×	
Lin et al. (2001)		×						×	×			
Vial et al. (2000)		×	×		×	×			×	×	×	
Kang et al. (2000)									×			
Letzel et al. (1997)	×	×			×		×		×		×	
Drahoš et al. (1992)										×		
Drahoš et al. (1991)		×			×						×	×
Franca et al. (1991)				×					×	×	×	
Matsui (1986)		×		×	×	×						
Tutu (1982)				×								