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Prediction of flow regimes transitions in bubble columns using passive acoustic measurements

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ABSTRACT

Passive acoustic sound, measured by a hydrophone in an air–water bubble column, is used to study the hydrodynamics of the unit. The recorded measurements taken at different superficial gas velocities are processed using both spectral and chaos-based techniques in order to characterize the column flow regimes and to predict the transitions points. These processing tools were supported by digital video imaging of bubbles motion inside the column. The results of data analysis indicate the applicability of passive sound measurements to identify flow regimes in the bubble column. In this regard the analysis of sound spectra gives a useful qualitative comparison of flow regimes. Chaos-based techniques, on the other hand, are more successful in predicting the transition points between the homogenous and the churn-turbulent flow regimes in the column. The critical gas velocities of the transition are associated with a marked change in some of the calculated chaotic invariants of sound pressures. The calculated superficial gas velocities of the critical points are also found to be consistent with experimental observations. Moreover, a useful visualization of the dynamics induced in the column by the alternation of small and large bubbles is possible through the inspection of phase-space trajectories reconstructed from time-series measurements. The shape and size of the trajectories are closely linked to the size distribution of bubbles, and they change as the flow moves from one regime to an other.

1. Introduction

Owing to their simple construction and their good heat and mass transfer, bubble columns are widely used for gas–liquid reactions in such diverse fields as chemical, petrochemical, pharmaceutical and water treatment [1,2]. Notwithstanding their operational advantages, bubble column hydrodynamics are complex and are characterized by different flow patterns depending on gas flow rate, physico-chemical properties of the gas–liquid system, gas distributor design, column diameter, etc. In this regard, homogeneous (bubbly) flow, transition regime and heterogeneous (churn-turbulent) flow are successively observed with increasing superficial gas velocities [3]. Another flow pattern, the slug flow regime, was also reported for small diameter columns [2]. The substantial amount of experimental work in the last decades on bubble columns has allowed an accurate description of the cited flow regimes. The homogenous regime is encountered at low gas velocities when the gas from the sparger is uniformly distributed. This regime is characterized by a narrow bubble-size distribution and by a radially uniform gas hold-up. In this regime both the distributor and the properties of the gas–liquid system play a dominant role in bubble-size distribution and gas hold-up profile [4,5]. The heterogeneous regime, on the other hand, is encountered at high gas flow rates. Small bubbles coalesce to produce relatively larger bubbles. This regime is therefore characterized by a wide distribution of bubble size and increased radial gas hold-up profile. The hydrodynamics in this regime are therefore more influenced by the bubble induced turbulence than by the distributor [6]. The two flow regimes are separated by a transition regime characterized by the development of local liquid circulation patterns [7]. Since it is often desirable to operate under homogenous conditions, it is of importance to accurately determine the limits between the flow regimes. Various methods were used in the literature to determine the flow regime transitions. Gas hold-up measurements using simple manometers represents the simplest method. The curve representing the variations of gas hold-up with superficial gas velocity exhibits a pronounced maximum reflecting the transition between the homogenous and the heterogeneous regimes [8]. More advanced measurement techniques were also used in the literature. These include for instance wall pressure signals [9], local gas hold-up fluctuations with optical or resistive probes [10], chordal void fraction fluctuations with absorption techniques [11], temperature fluctuations [12], optical measurements [13], ultrasonic methods [14] and the electrical capacitance tomographic method [15]. Paral-

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lel to these measurements techniques, various time-series analysis tools were used to characterize the flow regimes from the recorded experimental signals. These include statistical [16,17], spectral [7] and deterministic chaos [7–18] methods. These different processing tools are not necessary unrelated. van der Schaaf et al. [19], for instance, have shown that a direct relationship exists between chaos analysis (i.e. Kolmogorov entropy) and power spectral density of pressure drop fluctuations in a fluidized bed. Ruthiya et al. [20], on the other hand, showed that changes with gas velocity of both the coherent standard deviation and the average frequency of the pressure fluctuation data can be used to mark flow regime transitions in slurry bubble columns. They also showed that a direct relationship exists between the average frequency of pressure fluctuations and the Kolmogorov entropy.

In this paper, we investigate the flow regimes and regime transitions in bubble columns from a different perspective. Passive sound measurements from an air–water bubble column are recorded and analyzed using a combination of spectral and chaos-based techniques. These techniques were proved to be effective in previous studies involving wall and local pressure drop measurements [7,17,18]. These processing tools are assisted by digital imaging of bubbles motion inside the column. The objectives of this work are two fold: the first objective is to test the applicability of sound pressures to characterize flow regimes in the column and to predict flow transitions. The second objective of this work is to evaluate the efficiency of these processing tools for the analysis of sound pressures. Given the large number of tools available in the literature for time-series analysis, the strategy followed in this paper is not to try to apply many of these techniques but rather to see if methods of different theoretical backgrounds can yield consistent conclusions on the characterization of flow regimes in the column. It should be noted that at this point of our research the choice of these processing tools rather than a direct analysis of pressure fluctuations (e.g. coherent standard deviation) is dictated by the known difficulty in extracting hydrodynamics information, such as bubble-size distribution and gas hold-up, from passive acoustic signals. This is probably one of the reasons why these methods are not commonly used in multi-phase systems. In the following, and before the details of the experiment and the results analysis are discussed, we present a brief overview of the theory of passive sounds in gas–liquid systems.

2. Passive acoustic emissions

Gas bubbles entrained in a liquid are known to generate large sound pressures that are audible by the human ear i.e. passive acoustic emissions [21]. The sound is the result of oscillatory motion of the bubble wall due to its volume pulsations. These pulsations are excited by changes in the external or internal pressure on the bubble. The excitation can be due to many factors such as bubble formation, bubble coalescence or splitting, rising bubbles and flow past bodies [22]. Minnaert [21] was the first to study the sound of air bubbles formed at a nozzle. The author also derived the following relation that relates the natural frequency of oscillation to the bubble radius,

$$f_0 = \left(\frac{3\gamma P_0}{\rho}\right)^{0.5} \frac{1}{2\pi r} \quad (1)$$

where f_0 is the natural frequency of bubble oscillations, P_0 is the pressure of the surrounding liquid, ρ the liquid density, γ the ratio of specific heat capacities of the gas and r is the bubble radius. Plesset [23], later, showed that the cited equation should be corrected to include the effect of surface tension. However, for an air–water system, such as the one studied in this paper, the effect of surface tension can be generally neglected. This equation has been exploited by a number of authors to study the oscillatory behavior of bubbles and to extract bubble-size distribution in systems other than bubble columns [24–31]. A review paper on the use of passive acoustic measurements in chemical engineering processes is also given by Boyd and Varley [30]. In bubble columns applications, Boyd and Varley [31] presented a study of the measurement of gas hold-up from low frequency acoustic emissions. Recently, Al-Masry et al. [32] studied the sound pressures in a bubble column recorded by a miniature hydrophone. The authors used statistical analysis to estimate the bubble-size distribution and gas hold-up. Later the same authors [33] investigated the bubble distribution in the column when anti-foams were introduced in the air–water system. The authors showed that the addition of anti-foams increase the coalescence of bubbles and this was reflected in the sound pressures measurements and bubbles distribution.

3. Experimental

An overview of the experimental set up is shown in Fig. 1. The test section of the column consisted of a transparent acrylic resin of 150 mm internal diameter and 1.5 m height. The gas distributor consisted of a ring sparger with six legs star-like cross with 85 holes and 1 mm diameter equally distributed. Compressed air cylinders at room temperature were used for a stable source of air supply. The gas flow rate was controlled using thermal mass flowmeters controllers (Omega FMA2613). A miniature hydrophone (Bruel & Kjaer, type 8103) was used to record the sound pressure fluctuations. The hydrophone was placed in the center of the column at a depth of 40 cm from the gas distributor. The hydrophone signals were pre-amplified by Bruel & Kjaer type 2635 charge amplifier. Acoustic pressures were digitized as voltages using Data Translation data acquisition system. In each experimental run the gas flow was set and the column was operated for several minutes to ensure that the flow has reached steady state before the acoustic signal was recorded. The superficial gas velocity was varied up to 6.6 cm/s. The sound measurements were collected at different gas flow rates using a sampling rate of 20 kHz and a capture time of 10 s. Since the bubble oscillation may last at the most 20 ms, the 10-s long data signal may contain several bubble pulsations. The recorded signal was later analyzed using a variety of tools including the Chaos Data Analyzer [34]. A total of 2×10^5 points were collected for each experimental run. However, not all this large recorded signal could be used for the computations, and the analysis was limited to 2×10^4 points. But in order to check the consistency of the results obtained, the original recorded signal was divided into different segments each one of 2×10^4 points and the calculations were repeated for some segments in order to check that they yield identical results. This deemed important especially for computing some chaotic invariants such as the Kolmogorov entropy and the correlation dimension.

4. Results and discussion

We first present our observations of some of the main patterns seen in the column as the superficial gas velocity is increased. At a very low gas flow rate of around 1.0 l/min (U_g = 0.1 cm/s) the gas is not well sparged, and mainly bubble swarms are seen to form in the column. At the gas flow rate of 10 l/min (U_g = 1.0 cm/s), small bubbles of relatively uniform size rise in the column in a rather orderly way. When the superficial gas velocity increases to 1.8 cm/s, a slow circulation of the liquid can be seen. This circulation forces some of the bubbles to move downward. Most of bubbles in this stage have more or less a uniform size. When the gas velocity further increases above 2.8 cm/s and up to 4.7 cm/s,