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Measurement of properties of chaotic bubble paths

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ABSTRACT

The chaotic properties of bubble paths in bubble chain have been analysed. The bubbles have been generated from a brass cylindrical nozzle with inner diameter equal to 1 mm and placed at the centre of the bottom of rectangular tank (300 × 150 × 500 mm), which was filled with distilled water. Bubble departure diameter was about 5.5 mm. The mirrors system and high speed camera have been used for determining the 3D paths of subsequently departing bubbles. The chaotic changes of bubble path shapes have been observed. Bubble chains obtained for three different air volume flow rates have been analysed. The bubble departure frequencies were adequately 9.4 Hz, 11.6 Hz and 12.7 Hz. The method of Hurst exponent estimation for chaotic bubble paths has been proposed. The Hurst exponent has been calculated for bubble path projections on two orthogonal planes–parallel to the tank walls (shorter and wider). Obtained Hurst exponents confirm that bubble paths have deterministic chaos character. Also, sensitivity of the chaotic bubble paths on initial conditions and the structure of liquid flow around the bubble chain has been discovered. Proposed method allows us to detect anomalies of bubble paths. There has been discovered that predictability of bubble path projection varies depending on the plane which has been chosen for the projection. We can conclude that the method proposed in the paper is suitable for measurement of chaotic bubble path properties.

1. Introduction

The study of bubble dynamics is crucial to understand the phenomenon of bubble-fluid and bubble–bubble interactions. According to [1] the bubble motion and bubble shape are controlled by deterministic forces such as body force, drag force and the complex non-linear forces generated by liquid motion around bubbles. The path of bubble rising freely in stagnant fluids has been studied by many scientists over the past years [2,3]. It has been proven that the bubble diameter as well as the Reynolds number play an important role in shaping the bubble paths. When the Reynolds number exceeds 600, the rectilinear bubble path change into zigzag or helical path [4]. For $D < 1$ mm the bubble paths are similar to a vertical line but for $D > 1$ mm the bubble at first flows along the vertical line and then it develops a zigzag motion [5,6]. In certain conditions paths change into a spiralling circular motion [7]. In the paper [8] it has been shown that the mean lateral displacement of the bubble compared to the bubble diameter has two maxima: the first one ($D \sim 2$ mm) – when the bubble path is similar to periodic function, and the other one ($D \sim 4$ mm) – when the random lateral displacement of the bubble is observed. In papers [2,3] the authors show that the bubble shape, motion and velocity strongly depend on the initial conditions.

When the bubble departure frequency is high enough the bubble flow cannot be treated as in the stagnant fluid. In this case the interaction between bubbles has a significant impact on the bubbles flow dynamics. Aboulhasanzadeh and Tryggvason [9] studied freely moving bubbles and interactions between them in bubbly flow. The study of Corchero et.al [10] focused on the investigation of the effect of the non-constant volumetric gas flow rates on the bubble flow formation. An numerical attemption and experimental studies on the path and wake of a gas bubble in liquid were done by Mougin [11], Ellingsen [12] and Vries [13].

In paper [1] the analysis of interaction between bubbles rising in a chain is presented. The authors showed that for low bubble departure frequencies the trajectories were nearly identical, however for much higher frequencies, bubbles rose identically to a certain point. In the papers [15–17] it has been shown that such quantities as: bubble departure frequency, bubble departure diameter, bubble shape and its deformation, gas pressure fluctuations in the nozzle, bubbles interaction, bubbles coalescence and bouncing, structure of liquid flow around the bubbles and bubble chain change chaotically during the freely rising bubbles in liquid. Mosdorf and Wyszkowski [14] show that the interaction between bubbles can create the self-organising structure of bubble

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Nomenclature

D	bubble departure diameter [mm]
$f(x)$	Johnson Su distribution
q	volume flow rate [l/min]
k	time delay [s]
H	Hurst exponent
Ss	skewness of Johnson Su distribution
T	water temperature [°C]
X_t	time series
X, Y, Z	coordinate system

Greek letter

σ	standard deviation
μ	average value of recorded data

departure from a nozzle outlet. The stability of alternative bubble departures depends on the distance between nozzles, their arrangement and the air volume flow rate.

The main aim of the paper is the presentation of new method of identification of the chaotic bubble paths properties in bubble chain formed by subsequently departing bubbles. In general, it is well-known that bubble paths strongly depend on the initial conditions of their flow [3]. In the present experiment the bubble chain above nozzle outlet modifies the bubble departure initial conditions. However, when the bubble paths inside the bubble chain are chaotic, then their dynamic properties can be treated as indicators of the bubble chain dynamics. The present paper focuses on the measurement of dynamic properties of chaotic bubble paths. The detail analysis of fluctuations of initial conditions of bubble movement has not been discussed in the paper.

In the experiment the bubbles have been generated from a brass cylindrical nozzle with inner diameter equal to 1 mm placed in the centre of the bottom of the rectangular tank which was filled with distilled water. The mirrors system and high speed camera have been used for determining the 3D paths of subsequent bubbles. Bubble paths obtained for three different air volume flow rates have been analysed. The method of Hurst exponent estimation for chaotic bubble path has been proposed. The Hurst exponent has been calculated for trajectory projections on two orthogonal planes–parallel to the tank walls (shorter and wider).

2. Experimental setup and bubble paths identification

In the experiment the bubbles were generated from a brass cylindrical nozzle with inner diameter equal to 1 mm, placed in the centre of the bottom of rectangular tank (300 × 150 × 500 mm) which was filled with distilled water ($T = 21 \pm 1$ °C). The scheme of the experimental setup is shown in Fig. 1. On the left and right side of the tank two LED light panels were placed. "Milk" glass has been used to disperse the light and to get a uniform background. The movement of the bubbles was recorded with a high speed camera, the Phantom v1610 with 600 fps (1280 × 800 pixels). By using two flat mirrors and one which was formed from two mutually perpendicular mirrors the two scenes were obtained on a single frame of the video recorded by the camera. Three air volume flow rates: 0.0228 l/min, 0.0333 l/min and 0.0425 l/min have been examined. The average bubble departure frequencies were adequately equal to: 9.4 Hz, 11.6 Hz and 12.7 Hz.

The location of the coordinate system (in which the coordinates of mass centre of the bubbles were calculated) as well as the scheme of obtaining the two images of a single bubble path on mirror (see 8.1 in Fig. 1b) have been shown in Fig. 1b.

The mean values of bubble departure diameters were calculated based on the measurement of diameter of 100 subsequent bubbles. For different air volume flow rates the bubble departure diameters were adequately: 5.2 ± 0.1 , 5.5 ± 0.1 , 5.7 ± 0.1 mm which allowed us to obtain the chaotic paths of bubbles (according to [21]).

In the experiment only the average air volume flow rate has been controlled. It means that all parameters characterising the departing bubbles such as: the bubble departure diameter and the bubble departure velocity as well as the instant air volume flow rate fluctuated during the experiment. In Fig. 2 it has been shown the consecutive images of bubble departure for air volume flow rate $q = 0.0425$ l/min. The small fluctuations of initial conditions cause that 0.11 s after bubble departure the different bubbles can rotate in the opposite direction (left Fig. 2a, right Fig. 2b).

In our experiment bubbles departed in non-stagnant water. In this case the estimation of bubble Reynolds number required the knowledge about the liquid velocity around the bubble chain. Such velocity was not measured in the experiment.

Image filtration was used to remove undesirable elements from bubble images such as noise or distortion. In order to obtain a noise

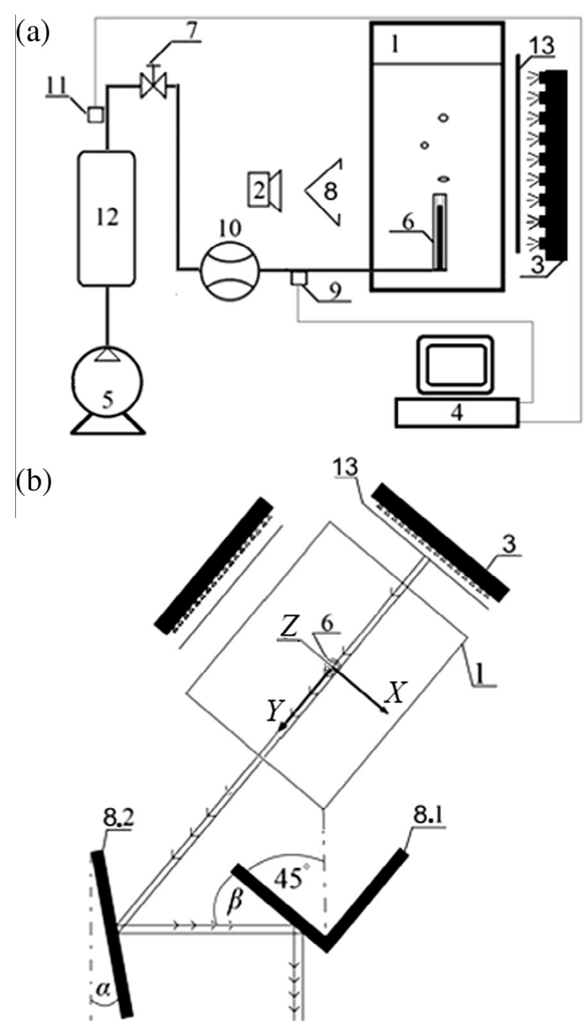

Fig. 1. Scheme of the experimental setup: (a) experimental setup, (b) mirror locations. 1 – glass tank, 2 – camera, 3 – light panel, 4 – data acquisition station, 5 – air pump, 6 – nozzle, 7 – air valve, 8 – mirrors, 9 and 11 – pressure sensors, 10 – flow meter, 12 – air tank.