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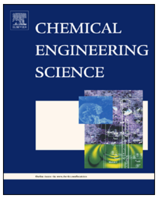

Stability of periodic bubble departures at a low frequency

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HIGHLIGHTS

- Dynamics of bubble departures from glass nozzle has been studied.
- Stability loss of periodic bubble departures has been investigated.
- Stability of periodic bubble departures depends on the volume of air supply system.
- Non-linear gas compression is responsible for chaotic bubble departures.

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ABSTRACT

The dynamics of bubble departures (at a frequency of $f=3$ Hz) from a glass nozzle submerged in a tank filled with distilled water has been experimentally and theoretically studied. The volume of the system that supplies air to the nozzle (plenum chamber volume) and the air volume flow rate were changed in the experiment. The air pressure, bubble paths and liquid flow inside the nozzle were simultaneously recorded using a data acquisition system and a high-speed camera. It was shown that an increase in the plenum chamber volume leads to an increase in the intensity of the occurrences of chaotic changes in the subsequent waiting times. The analysis of the mechanism of the stability loss of the periodic bubble departures was based on changes in the time of the air pressure, the depth of the liquid penetration into the nozzle, the time of the bubble growth, the waiting time, and the bubble paths and their sizes, which is presented in this paper. The results of the analysis are compared with simulations that are based on the models of bubble growth and liquid flow inside the nozzle during the waiting time. It was shown that the air pressure rise, Δp_l, during the waiting time is a non-linear function of the gas pressure after the bubble departure and the liquid velocity around the nozzle outlet. The nonlinearity of Δp_l increases when the plenum chamber volume increases, and it decreases when the air volume flow rate increases.

1. Introduction

There are a substantial number of papers that report the non-linear behaviours of the bubbling process (Zun and Groselj, 1996; Kovalchuk et al., 1999; Zhang and Shoji, 2001; Mosdorf and Shoji, 2003; Cieslinski and Mosdorf, 2005; Vazquez et al., 2008; Ruzicka et al., 2009a; Stanovsky et al., 2011; Mosdorf and Wyszkowski, 2011). There are at least two groups of phenomena that are responsible for the occurrence of non-linear behaviours of bubbles. The first group is connected with the behaviour of the flow of bubbles in the liquid (Peebles and Garber, 1953; Hughes et al., 1955; Davidson and Amick, 1956; Davidson and Schüler, 1960; Kling, 1962; McCann and Prince, 1971; Zun and Groselj, 1996; Kyriakides et al., 1997). The second group is connected with processes that directly concern the bubble departures and that occur in the gas supply system. The influence of the plate thickness, surface tension, the viscosity of the liquid and the height of the liquid column on the depth of the liquid penetration into the nozzle has been reported in the previous papers (Antoniadis et al., 1992; Dukhin et al., 1998a,b; Kovalchuk et al., 1999; Ruzicka et al., 2009a; Stanovsky et al., 2011). The impact of the chamber volume and the height of the liquid over the orifice outlet on the frequency of the bubble departures have been investigated. It has been observed that the increase in the chamber volume increases the time period between two subsequent bubbles (Antoniadis et al., 1992). The increase in the height of the liquid over the orifice outlet leads also to an increase in the time period between subsequent bubbles (Stanovsky et al., 2011). The time period between the departing bubbles decreases when the number of gas–liquid interface oscillations decreases (Ruzicka et al., 2009a). The phenomena of the liquid movement inside the orifice or nozzle have been experimentally investigated

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and modelled by many researchers (Dukhin et al., 1998a,b; Kovalchuk et al., 1999; Ruzicka et al., 2009b).

Liquid weeping has been observed between subsequent bubble departures. The liquid weeping at orifices that have different diameters has been measured and modelled by Miyahara et al. (1984). The influence of the wake pressure on the liquid weeping at a single submerged orifice has been discussed in the paper (Zhang and Tan, 2000). It has been shown that the wake pressure at the orifice has a significant effect on the predicted values of the weeping flow rates and the weep points.

The bubble motion above the nozzle, gas and liquid flow inside the nozzle, the evolution of gas pressure in the plenum, the dynamics of the bubble growth, its size and departure velocity are correlated with one another. Therefore, an explanation for the nature of the chaotic bubble departures requires considering the interactions between the phenomena that occur in the plenum chamber and the motion of bubbles over the nozzle outlet.

In the experimental part of the present paper, the influence of the plenum chamber volume on the chaotic bubble behaviours has been analysed. A detailed analysis of the stability loss of the periodic bubble departures (at the mean frequency of 3 Hz) has been presented. In the other part of the paper, the model proposed by Ruzicka et al. (2009b) has been adopted for modelling the chaotic bubble departures. The mechanism by which the chaotic bubble departures appear in the model has been discussed and compared with experimental results.

2. Experimental setup, measurement techniques

In the experiment, bubbles were generated in a tank (300 mm × 150 mm × 700 mm) that was filled with distilled water using a glass nozzle with an inner diameter of 1 mm. The length of the nozzle was 70 mm. The schema of the experimental setup is shown in Fig. 1.

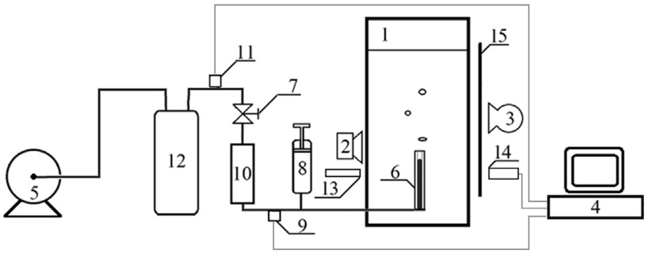

Fig. 1. Experimental setup: 1 – glass tank, 2 – camera, 3 – light source, 4 – computer acquisition system, 5 – air pump, 6 – glass nozzle, 7 – air valve, 8 – plenum chamber with the possibility of changing the volume, 9, 11 – pressure sensors, 10 – flow metre, 12 – air tank, 13 – laser, 14 – phototransistor, and 15 – semi-transparent glass.

The nozzle was placed at the bottom of the tank. The temperature of the distilled water was controlled by the digital thermometer MAXIM DS18B20 (with an accuracy of 0.1 °C) and, during the experiment, it was 20 ± 1 °C. The air pressure fluctuations have been measured with the use of the silicon pressure sensor Frescale Semiconductor MPX12DP, whose sensitivity was 5.5 mV/kPa. The air volume flow rate (q) was measured using the flow metre (MEDSON s.c. Sho-Rate-Europe Rev D, P10412A). The accuracy of the flow metre was equal to 5%. The plenum chamber volume was changed (in the range from 0.45 ml to 10.45 ml) by changing the volume of the syringe (8). The accuracy of the volume measurement was ± 0.5 ml, and it was defined by a syringe scale. The air pressure was recorded using a data acquisition system Data Translation DT9804 with a sampling frequency of 2 kHz and 16 bits of resolution.

Bubble departures and liquid movement inside the nozzle were recorded with a high speed camera, the CASIO EX FX 1. The data and video have been recorded after reaching a steady state by the system (approximately 15 min after the change in the air volume flow rate). The duration of each video was 20 s. The recorded videos (600 fps) in the grey scale have been divided into frames (432 × 192 pixels). An example of such frames is shown in Fig. 2.

The depth of the liquid penetration inside the nozzle was measured using a computer programme, which analysed the subsequent frames. The programme was prepared by investigators with the use of the Lazarus environment. They counted the number of pixels that had a brightness of greater than a certain brightness threshold on the each frame, along the nozzle wall. The threshold was adjusted for each video by comparing the results of the computer calculations with visual observations of the depth of the liquid penetration into the nozzle in the video. The size of 1 pixel was estimated to be 0.14 mm and is based on the known diameter of the nozzle. Approximately 12,000 frames were used to reconstruct the time series for each steady state of bubble departures.

The Sobel filter based on the convolution of the image with a small, integer-valued filter has been used to identify the bubbles on the frames (Hedengren, 1988). Because the Sobel algorithm identifies only the edge of the image of the bubble, the interior of the detected bubble was filled by black pixels. Finally, each bubble was visible in the frame as a set of black pixels. The path of each bubble was reconstructed by tracking the trajectory of mass centre of its 2D image in subsequent frames. The vertical position of the mass centre of the bubble image was reconstructed in the range of 5–35 mm over the nozzle outlet due to imaging and software limitations.

The depth of the liquid penetration inside the nozzle and the air pressure changes were recorded with different sampling frequencies, which were equal to 600 Hz (for video) and 2 kHz (for the pressure measurement). For the synchronisation of these time series, the adjustment of the sampling frequency was required. The pressure signals were resampled to 600 Hz, and

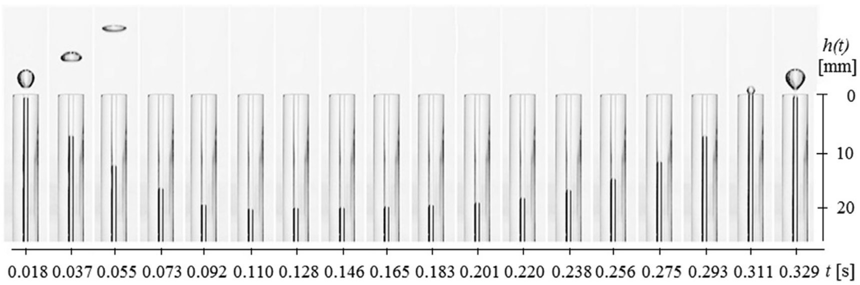

Fig. 2. Liquid penetration into the nozzle and bubble departures for the air volume flow rate q=0.00632 l/min. The time between the frames shown in figure is equal to 0.0183 s. In the recorded video, the time between the frames was equal to 0.001667 s.