Liquid penetration inside glass nozzle during bubble departures in water

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Abstract. Liquid penetration into the glass nozzle with inner diameter of 1 mm during the bubble, departures in distilled (surface tension = 65 mN/m) and not distilled (surface tension = 72 mN/m), water was investigated. It has been shown that dynamics of liquid movement inside the nozzle depend on the water surface tension. Maximum value of liquid penetration inside the nozzle is different for distilled and not distilled water. In not distilled water the depth of liquid penetration into the nozzle depends on air volume flow rate. For desilted water this value is constant.

1. Introduction

A process of gas flow in the liquid is very complex academic problem. This process is researched in many scientific fields: chemical and process engineering, pharmaceuticals, food production, fertilizer production and metal processing. Understanding a phenomenon of the process of gas flow in the liquid especially the dynamic of chaotic and periodic bubble departures allows to better control of process associated with aeration or saturation. The way of bubble departures influence on bubble trajectories and bubble chain formation (which is connected with bubbles coalescence), period between subsequent bubble or bubble size.

There are many papers, which describe non-linear bubbles departures [1,2,3,4,5]. Two groups of phenomena are responsible for the occurrence of chaotic bubble departures: behaviour of the flow of bubbles in the liquid [1,4,6,7] and process connected with changes of pressure in gas supply system during bubble departures [4,5,8,9]. On the one hand, nonlinear changes of pressure in gas supply system are connected with nonlinear dynamics of gas–liquid interfaces inside the nozzle. On the other hand the nonlinear behaviour of gas–liquid interfaces is sensitive on physico-chemical surface properties such as dynamic viscosity or surface tension force [8]. Nonlinear behaviour of gas-liquid interface modify: bubbles size, period between subsequent bubbles and trajectories of departed bubbles.

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The bubble departure time is divided into two periods: bubble growth time and waiting time [5,8,11]. During the waiting time, at first the nozzle is penetrated by the liquid, afterwards the liquid is removing from the nozzle. The process of liquid penetration depends on changes of pressure in gas supply system and boundary conditions such as e.g. chamber volume, the height of the liquid column over the orifice, the plate thickness, surface tension, or the viscosity of the liquid. The influence of: the air volume flow rate, air chamber volume, the height of the liquid column over the orifice, the plate thickness, surface tension, the viscosity of the liquid on the depth of the liquid penetration into the orifice has been reported in previous papers [4,9,10,11,13]. In the paper [4] it was shown that increase of volume chamber causes increase of total time of bubbling. Decrease of liquid column over the orifice causes decrease of total time of bubbling and bubble waiting time. Likewise, it was shown that increase of liquid column modifies the value and velocity of meniscus oscillation in its maximum position in the orifice. Modification of viscosity reduces total time of bubbling, but does not effect for bubble waiting time. In studies, the influence of surface tension on nonlinear behaviour of gas-liquid interfaces is inconclusive. Therefore in the present paper this problem was analysed.

In present paper the liquid penetration into the glass nozzle with internal diameter of 1 mm has been study. In experimental investigations two kinds of water: desalted ($\gamma = 65$ mN/m) and non-distilled water ($\gamma = 72$ mN/m), were used. The temperature of liquid was equal to 20°C. During experimental investigations, the air volume flow rate was changed. In order to measure the depth of liquid penetration into the nozzle, for subsequent bubbling cycles, videos were recorded, using high speed camera. Simultaneously, the fluctuations of pressure in gas supply system were measured. In present paper it has been shown, that the maximum value of liquid penetration inside the nozzle is different for desalted and non-distilled water. In non-distilled water the depth of liquid movement depended on air volume flow rate. In desalted water the depth of liquid penetration into the nozzle was constant during the changes of air volume flow rate.

2. Experimental setup

In the experimental investigations, bubbles were generated in a tank (300 x 150 x 700 mm) from the glass nozzle with an inner diameter of 1 mm. The length of the nozzle was equal to 75 mm. Bubbles were generated to the distillate and non-distillate water. Water was changed during subsequent investigations. Surface tension, of both kinds of water, was analysed using STA 1 Tensiometer. Surface tension of distillate water was equal to 65 mN/m and non-distillate water was equal to 72 mN/m. The schema of the experimental setup is shown in Fig. 1.
The glass nozzle was placed at the bottom of the tank. The temperatures of the distilled and non-distilled water were controlled by the digital thermometer MAXIM DS18B20 (with an accuracy of 0.1°C). Temperature of water, during the experimental investigations, was obtained on value equal to 20±1°C. The air volume flow rate was measured by using flow meter – BRONKHORST (4). The air volume flow rate was set by using air valve (5) in the range of 0.005 l/min to 0.29 l/min for distilled water and for non-distilled water was changed in the range of 0.005 l/min to 0.038 l/min. Ranges of air volume flow rate were selected so that the process of liquid penetration into the nozzle was visible. The gas supply system was powered by air pomp (8). The pressure in air tank (6) was set by proportional pressure reducing valve Metalwork Regtronic (7). The adjustable pressure range is from 0.05 to 10 bar, with accuracy equal to 0.5%. During the experimental investigations the air pressure was set as 0.3 bar. Air pressure fluctuations were measured with the use of the silicon pressure sensor Frescale Semiconductor MPX12DP, whose sensitivity was 5.5 mV/kPa. Time series of the air pressure changes were recorded by using a data acquisition system Data Translation DT9804 with a sampling frequency of 2 kHz and 16 bits of resolution.

The liquid movement inside the nozzle was recorded with a high speed camera, Phantom v1600. The duration of each video was 15 s. Videos were recorded (5000 fps) in the grey scale. Videos have been divided into frames with resolution of 512 x 768 pixels. Selected frames of changes of liquid movement inside the nozzle have been show in the Fig.2. The data and videos were recorded after reaching a steady state by the system (approximately 5 min after the change in the air volume flow rate). The laser – phototransistor system was used to synchronization of the data from high speed camera and from data acquisition station. The method of synchronization has described in the paper [12].

Figure 1. Schema of experimental setup: 1 – glass tank, 2 – nozzle, 3 – pressure sensor, 4 - flowmeter, 5 - air valve, 6 – air tank, 7 – pressure regulator, 8 - air pomp, 9 – light source, 10 – camera, 11 – screen, 12 – laser – phototransistor system, 13 – computer acquisition system.
Figure 2. Frames of videos contain liquid penetration into the nozzle for distilled water and air volume flow rate 0.026 l/min, duration between frames was equal to 0.01 s.

The single cycle of bubble departure was recorded on 445 frames (0.09 s). In order to better visualisation of bubble departure process, selected frames have been shown in the Fig.2. The duration between frames is equal to 0.01 s.

3. Results

Based on frames, changes of the depth of liquid penetration into the nozzle were estimated. The depth of the liquid penetration into the nozzle was measured by using a computer program, which was prepared by investigators with the use of the Lazarus environment. The program counted the number of pixels, which brightness was lower than certain brightness threshold on the frame. Pixels representing the presence of air in the nozzle had higher brightness than pixels which representing the water presence inside the nozzle. Changes of the depth of liquid penetration into the nozzle during single the cycle of bubble departure for distilled and not distilled water were shown in the Fig.3.

Figure 3. Changes of the depth of liquid penetration into the nozzle during single the cycle of bubble departure for distilled and not distilled water, $q = 0.026$ l/min. a) distilled water, b) non distilled water.
In the Fig. 3 reconstructions of the depth of liquid penetration for \( q = 0.026 \) l/min have been shown. The change of depth liquid movement for distilled water was shown in the Fig. 3a and in the Fig. 3b the change of depth liquid movement for non-distilled water was shown. In first the water is penetration nozzle. Next the depth of liquid penetration reaches a maximum value, then the liquid is removing from nozzle.

Curves in the Fig. 3 are different for each type of liquid. In the chart over the curve shapes of meniscus have been shown. Curves shapes are result of behaviour of meniscus during the liquid movement inside the nozzle. In both kind of liquid in first stage of liquid penetrations the shape of meniscus is spherical and it is directed upward. This shape of meniscus occurred in distilled water throughout the liquid movement inside the nozzle. The different situation is observed, when bubbles are generated to non-distilled water. When the depth of liquid penetration is close to maximum value, the meniscus becomes wavy. Next meniscus becomes spherical. Then meniscus begins to wander up to the nozzle edge.

In the Fig.4 time series of liquid movement inside the nozzle for both kind of water were shown.

![Figure 4](image)

**Figure 4.** Time series of liquid penetration into the nozzle for distilled and not distilled water, \( q = 0.026 \) l/min. a) distilled water, b) non distilled water.

In present cases (Fig.4) the chaotic character of bubbles departures was observed. Depths of liquid penetrations were not the same in subsequent cycles of bubble departures. The largest fluctuations in the depths of liquid penetration were occurring in the case, when the bubbles were generated in distilled water (Fig. 4b). Values of the depths were changed in the range of 4.4 mm to 5.4 mm. Minor fluctuations in depth of liquid penetration occurred, when the bubbles were generated in non-distilled water. Values of the depths were changed in the range of 4.7 mm to 5.2 mm.

In present paper the influence of air volume flow rate on the maximum value of the depth of liquid penetration into the nozzle for both kind of water was study. In the Fig.5 changes of maximum value
of the depth of liquid penetration into the nozzle, for distilled and non-distilled water and different air volume flow rates have been shown.

![Figure 5](image.png)

**Figure 5.** Changes of maximum value of the depth of liquid penetration into the nozzle for distilled and not distilled water and different air volume flow rates. a) distilled water, b) non distilled water.

In the Fig. 5a changes of maximum value of the depth of liquid penetration into the nozzle for distilled water have been shown. In this case the air volume flow rate was changed in the range of 0.005 to 0.026 l/min. In that designated range the liquid penetration in to the nozzle was observed. Maximum depths of liquid penetration for air volume flow rates, changed in the range of 0.008 to 0.026 l/min, were similar to each other and the value fluctuated in the range of 6.2 to 6.7 mm. For higher air volume flow rate the liquid movement inside the nozzle was not occurred. In Fig. 4b changes of maximum value of the depth of liquid penetration into the nozzle for non-distilled have been shown. The increase of air volume flow rate caused the decrease of maximal value of the depth of liquid penetration. The liquid penetration into the nozzle was not occurred, when the air volume flow rate was higher than \( q = 0.038 \) l/min.

**Conclusion**

In present paper the influence of surface tension on liquid penetration into the nozzle was study. It was shown that changes of kind of liquid causes changes of scenario of liquid penetration into the nozzle.
In the case, when bubbles are generated to non-distilled water, increase of air volume flow rate causes decreases of the depth of liquid penetration into the nozzle. During the stage of liquid penetration into the nozzle was observed the loss of spherical shape of meniscus, in its minimum position in the nozzle. The meniscus becomes flat and wavy. Then the meniscus begins to return to its previous shape and meniscus starts moving to the edge of the nozzle.

In the case when bubbles are generated to the distilled water, changes of air volume flow rate do not cause changes of the depth of liquid penetration into the nozzle. During the liquid penetration meniscus does not loss its spherical shape. The depths of liquid penetration into the nozzle in subsequent bubble cycles are more similar (constant air volume flow rate) than in case when bubbles were generated in non-distilled water.

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