Motion of a single vapor Taylor bubble in the vertical tube of small diameter

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Abstract. An experimental study of the dynamics of the Taylor vapor bubble in water and in an aqueous solution of lithium bromide at vapor saturation pressure was carried out. The Taylor bubble was formed after boiling-up of the overheated degassed liquid in 16 mm diameter tube. The study has shown that the dynamics of the vapor cavity during boiling up leads to a qualitative difference from the dynamics of the vapor bubble in a large volume. There are also qualitative differences in the nature of motion of the vapor bubble and that of the gas bubble. This is due to the fact that the mass of the gas bubble and the temperature of the liquid do not change during the rise near the bubble, whereas the mass of the vapor bubble and the temperature of the vapor in the bubble and the liquid near the bubble can vary significantly due to evaporation of the liquid and steam condensation. This is due to the change of bubble height and level of fluid in the tube. The liquid level in the tube depends on the height of the bubbles, but the height of the liquid level in the tube depends on the volume of the bubbles.

1. Introduction

The classical problem of the rise of a large gas bubble (Taylor bubble) in a tube with liquid is of practical importance for many industries, energy and oil production [1-8]. To solve this problem it is very important to study the influence of heat-mass transfer processes between the vapor bubble and the liquid on the shape and velocity of the rising Taylor bubble in the absorbent solution. In this case, it is necessary to take into account the heat release during absorption and the change in the concentration of the absorbent in the vicinity of the bubble. To model the process, it is necessary to choose the main factors from numerous influencing parameters. The correctness of the choice can be determined by comparing the results of calculations with experimental data. However, if there is a discrepancy between experimental data and calculations, validation of the processing method of the primary data is required. For example, when determining the geometrical parameters of a rising small spherical vapor bubble, it is necessary to take into account that, due to the deformation and rotation of the bubble, the method of processing the primary data obtained from photographing the bubble can change fundamentally. Figure 1 shows the video frames of the vapor bubble rising in aqueous LiBr solution of 56 wt% at temperature $T_0 = 297$ K. Vapor at temperature $T_{v0} = 332$ K was fed through the capillary tube in the volume of liquid. The vapor bubble volume $V$ was determined by processing the bubble image on video frames by formula:

$$V = \sum_{i=1}^{4} V_i, \quad V_i = \frac{1}{4} \cdot \frac{4}{3} \cdot \pi \cdot a_i \cdot b_i^2$$
suggesting that the bubble can be divided into four parts; each of them can be considered an element of the ellipsoid with axes $a_i, b_i$. Experimental data on the vapor bubble volume $V$ (line 1) are shown in graph of Figure 1 as a function of time. The obtained data are compared with the results of calculations (lines 2, 3). The calculations were performed for spherical bubble with known value of pressure in the fluid near the bubble. Line 2 shows the results of calculations at the absence of absorption. Line 3 was calculated at absorption with constant flow rate of vapor on the surface of the bubble (at rising, the mass of vapor in the bubble decreased by 20 %). In the graph, we can see that there is significant discrepancy between the computation curves and experimental data, when the bubble approaches the liquid surface in the tube $(t > 500 \text{ ms})$. In this case, the discrepancy can be explained as an inaccuracy of the model, or as an incorrect method of primary data processing or bubble volume calculation. In the study of motion of single vapor Taylor bubble in a vertical pipe of small diameter, it is very important that its volume $V(t)$ for different times $t$ can be calculated both by the form seen on video frames and with sufficient accuracy by the change in the level of fluid in the tube $h_L$ using the simple formula:

$$V(t) = \left[h_L(t) - h_0\right] \cdot \frac{\pi D^2}{4}.$$  

where $D$ is the internal diameter of the tube, $[h_L(t) - h_0]$ is the change in the height of the liquid level in the tube relative to that without a bubble $h_0$. In this work to understand the mechanisms affecting the dynamics of lifting vapor Taylor bubble a series of experiments was carried out at saturation pressure in a small-diameter vertical tube with the vapor bubbles produced by boiling-up in water and in aqueous LiBr solution. Figure 1 shows a comparison of the results of calculations and experimental data for the dependence of the bubble volume $V$ on time $t$ of ascent of the vapor bubble at temperature $T_{v0} = 332 \text{ K}$ in 56 wt% aqueous solution of lithium bromide (LiBr) at temperature of $T_0 = 297 \text{ K}$.

![Figure 1](image-url)

**Figure 1.** The volume of the vapor bubble $V$ rising in aqueous LiBr solution vs. time $t$.

2. Experimental part

In the experiments, the Taylor vapor bubble was formed at superheated liquid boiling-up at the bottom part of the tube. The schematic diagram of experimental setup is shown in Figure 2. Calibrated glass tube 1 of length $L = 400 \text{ mm}$ and inner diameter $D = 16 \text{ mm}$ was filled with test liquid. Height $E$ of the
tube filled with liquid varied from 100 to 200 mm. The upper part of the tube was vacuumed by vacuum pump 3 through a vacuum trap. The pressure above liquid level was measured by vacuum manometer 2 (precision class 0.25). To overheat the liquid, the cylindrical electric heater with galvanic isolation from the solution was used. To place the electric heater at a height of 10 mm from the bottom, two short glass tubes with internal diameter of 8 mm were soldered to the tube. A tubular heater 9 (diameter 4 mm, length 16 mm) with copper weirs (diameter 3 mm) was placed in nichrome tube 8 (diameter 6 mm, wall thickness 0.5 mm). Chromel-alumel thermocouple was placed in the central part of the nichrome tube. The space between the tube and the heater was filled with finely dispersed electrically insulating paste with high coefficient of thermal conductivity. To create a hermetic seal between the heater and the working volume, vacuum rubber bushing 7 was used. Electric current to the electric heater from a DC voltage source 6 was supplied through copper current leads 10. Heat load varied from 30 to 500 watts (voltage from 0 to 30 V, maximum current 100 A). For determining the surface temperature of the nichrome tube 8 the thermocouple located in the heater was calibrated and empirical corrections related to the thermocouple position were determined.

![Figure 2. Scheme of experimental setup with designations of some values used in formulas](image)

To determine the volume of $V_B$, surface area $S_B$, position $h_B$, $h_C$, rising speed of vapor bubble $U$ and level of liquid in the tube $h_L$, the image of the working section was recorded at speeds up to 1000 fps on video camera 4. The temperature of liquid before boiling-up was controlled by infrared imager 5. At thermograms processing to determine the liquid temperature before boiling-up in different sections along the tube height, empirical corrections determined from the results of control experiments series were taken into account. Before each experiment the liquid was degassed.

The pressure in the vapor cavity $P$ was calculated taking into account the height of the liquid column above the bubble and the vapor pressure in the tube $P_0$:

$$P(t) = P_0 + \rho_L(T_L,c) \cdot g \left[ h_L(t) - h_B(t) \right],$$

(3)

where $c$ is the weight concentration, $g$ is the acceleration of gravity, $t$ is the time after boiling up, $h_B$ is the bubble head position, and $\rho_L$ is the density of the solution. The density for aqueous solution of LiBr with concentration $c$ at temperature $T_L$ was calculated according to data from work [9]. The volume of the vapor bubble $V_B$ was calculated by the formula (2), for small bubbles, the volume was additionally calculated by the formula (1). The mass of vapor in the bubble $m(t)$ calculated by formula:

$$m(t) = V_B \cdot \rho_B(T,P),$$

(4)
where \( \rho_B \) is the density of the vapor, which for temperature \( T \) and pressure \( P \) was calculated according to data from work [10]. According to the data on the position of the head \( h_B \) and bottom \( h_C \) of Taylor bubble, the values of velocities of the upper \( U_B \) and lower \( U_C \) boundaries of the bubble were determined by the formula:

\[
U_B = \frac{dh_B}{dt}; \quad U_C = \frac{dh_C}{dt}. \tag{5}
\]

3. Result and Discussion

A series of experiments was conducted to study the behavior of the Taylor vapor bubble in a tube with a diameter of 16 mm. The experiments were carried out in water and 58% aqueous solution of lithium bromide with different heights of the level liquid \( E \) in the pipe. The initial conditions for the Taylor bubble were varied by changing the value overheating \( T_h \) of the surface nichrome tube of the heater before boiling-up.

A study has shown that the dynamics of the rising vapor cavity after the boiling-up of liquid in a vertical tube of a small diameter for some initial conditions has a qualitative distinction from dynamics of a gas bubble rising in a pool. Qualitative differences in the nature of motion of gas and vapor bubble were also observed. They are due to the fact that the mass and temperature of gas in the bubble and the temperature of liquid near the bubble do not change at rising, while the mass and temperature of vapor in the bubble and the temperature of liquid near the bubble can vary significantly due to liquid evaporation of the and vapor condensation. One of these differences is that for vapor bubble in a tube of small diameter one may observe the pulsating mode for the vapor mass and bubble volume associated with a change in the height of the liquid level in the tube (Figure 3, Figure 5). This is due to the fact that the pressure in the bubble depends on the height of the liquid over the bubble while the height of the liquid level in the pipe depends on the volume of the bubble.

![Figure 3. Video frames after boiling-up of 58 % of aqueous LiBr solution in the tube.](image)

For example, Figure 3. shows video frames of the rising vapor bubble in an aqueous LiBr solution of 58 wt% at initial liquid level above the heater \( E = 128 \) mm, pressure in the volume \( P_0 = 518 \) Pa, solution temperature \( T_0 = 297.4 \) K, and the heater temperature before boiling-up \( T_h = 413.4 \) K. The time \( t \) in the frames was counted from the moment of boiling up. In these frames, one can see that when floating up, the height of the vapor bubble in nonmonotonic in time. Figure 4 shows how the velocity of the upper (line 1) \( U_B \) and lower (line 2) \( U_C \) parts of a bubble changes. After boiling-up for 50 ms, a rapid growth of the bubble and the formation of Taylor’s bubble are observed. It should be noted what the velocity at the top of the bubble \( U_B \) is several times higher than that at the bottom part.
of the bubble $U_C$. The maximum volume of the steam cavity is reached 183 ms after boiling-up, and the velocity of the rising coincides with the calculated value [2] for that of the gas bubble (line 3) $U = 0.13$ m/s. In the time interval from 360 to 400 ms, the velocity at the top of the bubble $U_B$ is less than zero, and there is a short-term pulsation of the bubble volume followed by a rapid collapse of the bubble. But as the bubble continues moving upward, the fluid level decreases, and the fluid near the bubble warms up due to the heat of condensation and absorption. A new phase of rapid bubble growth begins 250 ms after the collapse of bubble (frames $\geq 850$ ms) until the bubble reaches the free surface of the fluid. At this stage the velocity of the upper part of the bubble significantly exceeds that of the bottom part, presumably, due to intense liquid evaporation near the top of the bubble.

**Figure 4.** Velocities $U_B$ and $U_C$ for vapour bubble rising in aqueous LiBr solution vs. time $t$.

From the standpoint of physics there are no reasons to assume that the absorption and desorption can greatly change the processes nature in the rising vapor bubble. Therefore the pulsation effects which were observed for the Taylor vapor bubble rising in aqueous LiBr solution should be observed for bubble rising in the water. For example, Figure 5 shows video frames of the rising vapor bubble in water at initial liquid level above the heater $E = 98$ mm, pressure in the volume $P_0 = 2730$ Pa, solution temperature $T_0 = 295.6$ K, and the heater temperature before boiling-up $T_h = 361.1$ K. In these frames, one can see that for vapor bubble floating up in water, the height was nonmonotonic in time.

**Figure 5.** Video frames after boiling-up of water in the tube.

A graph of vapor mass $m(t)$ in the Taylor bubble vs. time $t$ for the rising bubble in tube of small diameter with water and with 58 wt% aqueous LiBr solution is shown in Figure 6. The graph shows a clear difference in the rise of bubble in an aqueous solution of LiBr and in water for the amplitude and duration of pulsations of vapor mass in bubble. Differences in dynamics of the vapor cavity for water and aqueous LiBr solution can be correlated with parameter $P_{th}/P_0$, which is equal to the ratio of the
pressure in the liquid near the $P_H$ heater before boiling-up to the vapor pressure in the tube $P_0$. In our experiments the value of parameter $P_H/P_0$ was of the order of $1.2 \div 1.5$ for water and $4 \div 5$ for a 58 wt% aqueous LiBr solution. Such difference between the values of this parameter may explain why the pulsations of vapor bubble in the tube with aqueous solution of LiBr were more noticeable than in pipe with water.

![Graph](image)

**Figure 6.** Changes in the mass of vapor $m$ in bubble rising in the tube.

For conditional narrow tube at pulsations of vapor Taylor bubble, in contrast to pulsations of the vapor bubble in a pool [11], the regimes with shock waves were not observed. This is probably due to the fact that the mass of the bubble rising in the tube differs by an order of magnitude from the vapor mass in the bubble, which is formed by the action of laser radiation, when shock waves are observed.

**Summary**
The study has shown that the dynamics of the steam cavity during boiling up qualitative differs from the dynamics of the vapor bubble in a large volume. There are also qualitative differences of the nature of motion of gas and vapor bubble. This is due to the fact that the mass of the gas bubble and the temperature of the liquid do not change during the rise near the bubble, whereas the mass of the vapor bubble and the temperature of the vapor in the bubble and the liquid near the bubble can vary significantly due to evaporation of the liquid and steam condensation. This is due to the change of bubble height and level of fluid in the tube. The liquid level in the tube depends on the height of the bubbles, but the height of the liquid level in the tube depends on the volume of the bubbles.

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