Experimental study of the motion and form of the vapor bubble floating in the annular channel at subatmospheric pressure

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Abstract. An experimental study was made of the dynamics of a vapor bubble floating up in an annular channel at subatmospheric pressure. A vapor bubble was formed after boiling of an overheated degassed liquid in an annular channel formed by two tubes with diameter of 25 mm and 16 mm. The study shows that the dynamics of the vapor cavity during the ascent of vapor bubble in an annular channel has qualitative difference from the dynamics of gas bubble and has much in common with the dynamics of Taylor vapor bubble floating in a small round tube. One of the features of the behavior of the vapor cavity in the annular gap is that in the pulsation mode at the collapse stage, it can disintegrate into several parts.

1. Introduction
Vapor bubbles, usually observed in boiling liquids, are a well-known phenomenon. In nature, there are geysers, hydrothermal vents and volcanic eruptions that are closely related to vapor bubbles. Vapor flow is one of the main flow regimes encountered in multiphase flow systems. The classical problem of raising a large gas bubble in a pipe with liquid is of practical importance for many industries and energy and oil and gas production systems [1-9]. The widespread distribution of vapor bubbles gives an extra impetus to their scientific research, but despite the apparent similarities, their physics can be very different from the physics of bubbles, which contain mainly gas dissolved in liquid. Vapor bubbles are extremely labile objects. They respond quickly even to minor changes in ambient pressure or temperature of the liquid with which they come in contact. A gas dissolved in liquid diffuses into vapor bubbles, causing phenomena, such as short and long-lived bubbles, observed in the same experiment under identical conditions. For all these reasons, experiments with vapor bubbles are complex and less effective than experiments with gas bubbles [1].

Replacing vapor compression refrigeration equipment with an absorption type installation can improve the efficiency of the used waste heat on ships. Due to strong vibrations and shaking on such vessels, the conditions for the operation of film-type absorbers may go beyond the operating parameters. Bubble-type absorbers are more suitable for operation under such conditions, since the refrigerant vapor bubbles are always inside the solution during absorption [2].

The coefficients of heat and mass transfer for bubble absorber are higher than for film absorber [3]. To calculate and increase the efficiency of bubble absorbers, it is important to simulate the processes that occur when steam bubbles rise in the absorbent solution.

To solve this problem, it is very important to study the effect of heat and mass transfer between vapor bubble and liquid on the shape and speed of an ascending vapor bubble in an absorbent solution.
It is necessary to take into account the heat during absorption and the change in the concentration of absorbent in the vicinity of the bubble. To model the process, it is necessary to choose the main factors from the set of influencing parameters. The correctness of the choice can be determined by comparing the results of calculations with experimental data. However, if there is discrepancy between the experimental data and the calculations, the verification of the method of processing the primary data is required.

In our experiments, we studied the growth and movement of vapor bubble in an annular channel, when the height of the liquid column above the heater creates a pressure commensurate with the saturation pressure at the liquid temperature.

2. Experimental part
In this paper, we conducted an experimental study of the dynamics of a vapor bubble of a channel emerging in an annular gap at a saturation pressure of liquid vapor above a free surface.

Figure 1 shows the scheme of the experimental setup. The liquid was poured into a calibrated glass tube 1 with a length $L = 700$ mm and an inner diameter $D = 25$ mm. To form an annular channel along the axis of the tube, a glass tube with a diameter of 16 mm and a cylindrical electric heater 7 with a diameter of 16 mm were installed. The upper part of the tube was connected through a vacuum trap to a vacuum pump 3. The pressure $P_0$ above the liquid was measured with a vacuum gauge 2 (accuracy class 0.5). To overheat the liquid, a cylindrical electric heater with galvanic isolation from the solution was used. A stainless steel nichrome wire heater (coil diameter of 14 mm and length of 160 mm) with copper current leads (diameter of 3 mm) was placed in a stainless steel cylindrical cup (diameter of 16 mm and wall thickness of 0.5 mm). The space between the spiral and the glass wall was filled with a finely dispersed electrically insulating filling with high coefficient of thermal conductivity. The height of the tube filling with liquid above the heater $E$ varied from 100 to 300 mm. The heat release level on the heater was set using an adjustable DC source 6 with a power of 1000 W (voltage from 0 to 30 V, maximum current 100 A).

![Figure 1](image)

**Figure 1.** Figure 1. Scheme of the experimental setup:

1 – glass tube, 2 – vacuum gauge, 3 – vacuum pump, 4 – video camera, 5 – thermal imager, 6 – DC source, 7 – electric heater, 8 – nichrome coil.

To determine the volume $V_B$, the surface area $S_B$, the position $h_B$, $h_C$, the speed $U$ of the vapor bubble and the liquid level in the tube $h_L$, we recorded the working section with two digital video cameras 4 at speed of up to 1000 fps. The fields of the frames intersected in the region near the liquid level, which was used to coordinate the position of the data obtained during the processing of the
frames. To synchronize the time frames of two cameras, a flash with pulse duration of 1.2 milliseconds was used.

At a tube glass density $\rho = 2.2$ g/cm$^3$, the calibration data correspond to the numerical solution to the problem of liquid column heating, taking into account heat losses through the cylindrical wall into the environment with heat transfer coefficient $\alpha \simeq 6 \div 8$ W/(m$^2$ K), if we assume that for tube glass, the wall thermal conductivity coefficient $\lambda \simeq 0.74$ W/(m$\cdot$K) and the specific heat $c \simeq 0.81$ J/(kg$\cdot$K).

Before the experiments, the liquid was degassed. The pressure in the vapor cavity $P$ was calculated by the formula (1) taking into account the height of the liquid column above the bubble and the vapor pressure in the tube $P_0$:

$$P(t) = P_0 + \rho_l(T) \cdot g \cdot [h_L(t) - h_b(t)],$$

where $h_b$ is the height of the bubble top, $\rho_l$ is the density of the liquid at the temperature $T_L$ [10, 11], $g$ is the acceleration of gravity, and $t$ is the time after boiling. The volume $V_b$ of the vapor bubble was calculated by the formula (2). The volume $V(t)$ for various times $t$ can be estimated by the shape of the vapor cavity visible on the video frames and calculated with sufficient accuracy by the formula:

$$V(t) = [h_L(t) - h_b] \cdot \frac{\pi \cdot (D_1^2 - D_2^2)}{4},$$

where $D_1, D_2$ are the diameters of the annular gap of the channel, $[h_L(t) - h_b]$ is the change in the height of the liquid level in the tube relative to the liquid level without bubble $h_b$. The vapor mass in the bubble $m$ was calculated using reference data for the vapor density $\rho_b$ depending on pressure $P$ and vapor temperature $T$ [11]:

$$m(t) = V_b \cdot \rho_b(T, P).$$

The temperature field of the liquid $T_L$ by the height of the tube before boiling was determined by thermograms obtained using the thermal imager 5. Calibration of thermograms of the thermal imager was carried out by determining the corrections necessary to determine the temperature of the liquid according to the temperature of the outer surface of the glass tube; taking into account the heat load and the warm-up time. The temperature above the heater $T(h)$ is well described by the exponential dependence (4):

$$T(h) = T_0 + (T_{II} - T_0) \cdot \exp \left( -\frac{h - h_{II}}{\delta} \right),$$

where $T_0$ is the initial temperature of the liquid, $T_{II}$ is the temperature of the liquid before boiling at the level $h_{II}$ of the upper edge of the heater 7.

3. Result and Discussion

The study shows that there are several characteristic regimes of the dynamics of the vapor cavity after boiling liquid in a vertical tube of small diameter, depending on the height of the initial liquid level in the tube and overheating before boiling. The height of the liquid column determines the amount of underheating of the liquid temperature to the saturation temperature near the heater. With an increase in overheating, the volume of superheated liquid above the heater also increases. The two main modes after boiling are the complete condensation of the vapor bubble after the growth stage and the monotonous increase in the volume of the vapor bubble. With small overheating before boiling and large underheating, condensation can occur without separation of the bubble from the heater. Similar regimes are observed under conditions of large volume (differences are only in the form of vapor bubble). With large overheating and small underheating, the vapor bubble may form on the heater, the length of which exceeds the length of the working tube.
Figure 2 shows video frames of vapor bubble floating-up in an annular channel. The initial height of the liquid level above the heater $E = 250$ mm, the pressure in the volume $P_0 = 2727$ Pa, the initial temperature of the liquid $T_0 = 22.3^\circ$C, and the temperature before boiling $T_H = 37.5^\circ$C. The time $t$ on the frames is counted from the moment of boiling. The temperature profile over the height above the heater is described by relationship (4) with $\delta \approx 26$ mm. The frames show that there is a non-monotonic change in the bubble size.

In [12], it was shown that an important parameter determining the nature of the motion and growth of vapor bubble is $P/P_0$, which is equal to the ratio of the pressure in the liquid near the bubble $P$ to the pressure above the liquid $P_0$. Figure 3 shows how the parameter $P/P_0$, the volume and mass of the vapor in the bubble change with the rise of single bubble in the annular channel over time. The arrows with numbers indicate the points in time corresponding to the frames in Figure 2. Figure 4 shows how the position of the apex $h_B$ and the bottom $h_C$ of the bubble in the channel changes. In this case, the rate of change of $h_C$ coincides with the calculated value for the rate of ascent of the gas bubble [13].

Figure 5 shows video frames of the emergence of vapor bubbles in an annular channel. The initial height of the liquid level above the heater $E = 250$ mm, the pressure in the volume $P_0 = 2900$ Pa, the initial temperature of the liquid $T_0 = 23.1^\circ$C, and the temperature before boiling $T_H = 48.2^\circ$C. The temperature profile along the height above the heater is described by dependence (4) with $\delta \approx 23$ mm. The figure shows that for the case of several bubbles, the difference from a single bubble is due to the influence of the lower bubble, the $P/P_0$ value increases, which is manifested in the duration of the "small size" stage of the upper bubble over time when the lower bubble has the "large size". So bubble A, and then bubble B, come out of the small bubble stage only near the free surface. The dynamics of
the volume and mass of bubble C is similar to the dynamics of a single bubble, but the difference is that when B and C collapse, they break up into several bubbles. A sharp increase in bubble C is observed after bubbles A and B emerge onto the surface ($t \sim 2.2$ seconds, the total volume and mass of the vapor sharply decrease). The peculiarity is how quickly bubble C grows out of many small parts, while bubble C has a complex shape and very wavy surface. In time interval of 2.2 - 2.6 seconds, the dynamics of growth of volume and mass of conglomerate C almost exactly repeats the dynamics of growth of single bubble in the interval of 0.4 - 0.8 seconds (see Figure 3).

**Figure 3.** The change in the mass of vapor in the bubble $m$ upon ascent in a tube of small diameter. Mode parameters for water: $H_0 = 250$ mm, $T_H = 37.5^\circ$C, $P_0 = 2727$ Pa, $T_0 = 22.3^\circ$C.

**Figure 4.** Change in the position of the apex $h_B$ and the bottom $h_C$ of bubble during the ascent of single bubble in the annular channel. The mode parameters are the same as in Figure 2.

A peculiarity of the $h_C$ change can be noted: there are areas where the velocity of the bottom of the bubble clearly coincides with the rate of rise of gas bubbles. However, there are other areas where this speed coincides with the speed of movement of the top of the lower bubble, that is, the bubble is involved in the movement of the liquid column caused by the lower the bubble. In the time interval from 0.9 s to 1.3 s for bubbles A and B, the "gas velocity" and for bubble C the bottom position change almost all the time with a constant speed. In the time interval from 0.3 s to 0.8 s, the position
$h_C$ of bubble A correlates with the position $h_B$ for bubble B. And similarly, in the region of 1.3 - 1.8 s, the position $h_C$ of bubble A and B correlates with the position for bubble C.

**Figure 5.** Video frames of successive ascent of vapor bubbles in water. Thermogram of the tube before boiling. Water temperature profile over the height of the channel. $E=250$ mm, $T_i=48.2°C$, $P_0=2900$ Pa, $T_0=23.1°C$, $\delta=23$ mm.

**Figure 6.** Change in the parameter $P/P_0$, the total volume and mass of vapor in the bubbles during the successive rise of vapor bubbles. The mode parameters are the same as in Figure 5.
Figure 7. Changing the position of the apex $h_B$ and the bottom $h_C$ of bubbles during floating-up in the annular channel. The mode parameters are the same as in Figure 5.

Conclusions
The study has shown that the dynamics of the vapor cavity floating in degassed liquid in the gap of the annular channel after boiling on the heater in the lower part of the channel corresponds to the dynamics of a single Taylor vapor bubble floating in a small diameter tube [12]. It has been found that during the ascent of the vapor bubble, there are regimes with non-monotonic changes in the size of the bubble, including regimes with fluctuations in the volume and mass of the vapor in the bubble. For pulsation regime to occur, it is necessary that the value of $P/P_0$ equal to the ratio of the pressure in the bubble to the pressure above the liquid $P_0$ exceed a certain threshold value. For water, the threshold value is 1.4. A feature of condensation in an annular channel, in contrast to Taylor bubble in circular channel, is that the vapor cavity can decay into several bubbles. As a result, the further stage of growth of the vapor bubble differs in complex shape and strongly wavy surface.

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