Experimental investigation of interaction between rising vapor bubbles on a vertical heater in acetone

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Abstract. Interaction between the rising vapor bubbles was investigated. The experiment was carried out in acetone under natural convection on a vertical heater 2.5 mm in diameter. Overheating of the heater surface before boiling-up varied from 30 to 120 degrees at saturation pressure from 20 to 40 kPa. Experiments have shown that the field of velocity and pressure behind a rising bubble has a strong influence on the growth dynamics of vapor bubble located below. This influence depends on the distance between the bubbles and growth phase of the upper bubble. When bubbles coalescence, high acceleration (100 m/s²) of particular parts of the interphase surface are observed. When the lower bubble coalescence with the upper bubble, the vapor spreads like a jet, and as a result, a conical perturbation is formed on the opposite side of the upper bubble.

1. Introduction
The replacement of vapor compression refrigeration equipment by a device of the absorption type makes it possible to increase the efficiency of using the waste heat use at sea-going ships. Due to strong vibrations and shaking on such ships, the conditions for operation of the film-type absorbers can go beyond the limits of the regime parameters. The bubble-type absorbers are more suitable for working under such conditions, since always in the process of absorption the bubbles of refrigerant vapor are inside the solution [1], and due to this, the heat and mass transfer coefficients for the bubble absorber are higher than for the film absorber [2]. The study of shapes and dynamics of single bubbles rising in liquid is a classical problem. There are many experimental and theoretical studies on floating of single gas and vapor bubbles [3-6]. In [4, 6], the shapes of single floating bubbles is sistematized depending on Reynolds, Galilei, Eötvös and Morton numbers. There are two regimes of symmetry loss by a spherical bubble [6]: one with minor asymmetry restricted to a flapping skirt; and another with marked shape evolution. In [5], the boundaries of violation of the gas cavity sphericity and formation of vortices in the back parts of cavities were determined based on numerical solutions and experimental results. To calculate and increase the efficiency of bubble absorber operation, it is important to simulate the processes that occur during interaction of vapor bubbles that float in inhomogeneously heated liquid. To identify the role of the main parameters that determine the process, it is necessary to investigate experimentally the mechanism of bubble collision and merging. To verify the reliability of simulation results on the growth, motion, and interaction of floating vapor bubbles in an axisymmetric temperature field, data obtained on a vertical heater can be used. The purpose of this work is to obtain experimental data on the shape and dynamics at interaction of bubbles floating in acetone.
2. Experimental apparatus and procedure

The scheme of experimental setup is shown in Figure 1. The vertical electric heater was located in a sealed vessel of $215 \times 215 \times 100$ mm, filled with 3.5 liters of working liquid (acetone). The working section was made of stainless steel tube with an outer diameter of 2.5 mm and inner diameter of 1.5 mm. The working section was heated by passing a direct current through the tube. Length of the heated section $H$ was 80.5 mm, electrical resistance of the section was 0.02 $\Omega$ at the temperature of 293 K. The tube surface was polished to reduce the number of active vaporization sites. The process of boiling and floating of the vapor bubbles was registered through a viewing window of 90 mm diameter by a Casio EX-F1 digital camera with a speed of 1200 fps.

![Figure 1. Schematic diagram of the experimental facility.](image)

Acetone was chosen for the research as liquid with stable properties, in which it is easy to achieve high superheating before boiling. The experiments were carried out under the conditions of natural convection at saturation pressure in the working volume from 20 to 40 kPa. Before the experiments, liquid in the vessel was degassed. The temperatures of vapor, liquid in the volume and heater were measured using the chromel-alumel thermocouples with the wire diameter of 0.1 mm. Also, the dependence of electrical resistance of the heater on temperature was used to determine the average temperature of the heater after boiling of liquid as a function of time. When the required value of wall overheating $\Delta T$ relative to the saturation temperature was achieved, a vaporization initiator, located near the heater at the distance of 10 mm from the lower edge of the working section, was switched on. A platinum wire with the diameter of 0.1 mm and length of 4 mm was used as the initiator. After the initiator was turned on and when it was overheated above 30 degrees, a "chain" of several rising vapor bubbles strung onto the test section was formed along the heater. The number of bubbles in the "chain" depended on the nature of interaction between them. When processing video frames for characteristic points visible in the vapor cavity, position $Y$ from the bottom edge of the heater, velocity $U$ and acceleration $A$ were determined.

Thermal calibration of the working section showed that a change in wall superheating $\Delta T(Y)$ depending on distance $Y$ can be presented in the form similar to that in [7]: $\text{Nu}_Y = 0.682 \cdot (\text{Ra}^*_Y)^{0.19}$, where $\text{Nu}_Y = q \cdot Y / [\Delta T(Y) \cdot \lambda]$ is Nusselt number, $\text{Ra}^*_Y = \text{Pr} \cdot g \cdot Y^4 \cdot \beta \cdot q / (\lambda \cdot \nu^2)$ is modified Rayleigh number, $g$ is gravity acceleration, $\alpha$ is local heat transfer coefficient, and thermo-physical properties of liquid: $\lambda$ is thermal conductivity, $\text{Pr}$ is Prandtl number, $\beta$ is thermal expansion coefficient, $\nu$ is kinematics viscosity. Figure 2 shows wall superheating $\Delta T(Y)$ for different values of thermal loads $q$. 
The graph also shows superheating $\Delta T(h)$ measured by a thermocouple located at distance $h = 28$ mm, which is used when referring to overheating before boiling $\Delta T$.

3. Discussion of results

Comparison of experimental data with data of [8] (Figure 3) showed that for overheating $\Delta T$ from 30 to 55 degrees a change in the shape of a single bubble and vapor cavity formed by interaction of two bubbles, moving along a vertical cylindrical heater, is similar to the shape of bubbles floating up in a large volume. The difference is that zigzag motions and oscillations of the symmetry axis of bubble, characteristic of the free rise regime, are suppressed in the presence of a vertical cylinder [9].

Figure 3. Comparison of the shape of steam cavity near the vertical cylindrical heater (a) with the shape of steam cavity in a pool (b) [4]: a) - acetone saturation pressure $P_s = 24.5$ kPa, $\Delta T = 45$ K; b) - water $P_s = 20$ kPa, $\Delta T = 40$ K.

The study showed that immediately after boiling up, a change in the shape, rate of growth and floating $U_0$ of the initially spherical vapor bubble agree with calculations for bubble growth $R(t)$ in a non-uniform temperature field [10, 11]. For example, Figure 4 shows the processing data for the shape and position of a bubble at overheating $\Delta T = 52$ K before boiling. Figure 4a compares The experimental data for the bubble curvature $R_b$ at the frontal point $A_b$ are compared in Figure 4a with the results of numerical calculation of $R(t)$ [6] obtained for the thickness of the superheated liquid layer of 1.5 mm. It is seen that at the initial stage of bubble growth ($0 \div 20$ ms), there is a good agreement between calculation results and experimental data. Figure 4b shows the data for the position of the frontal $A_b$ and back $B_b$ points of the floating bubble. Relationship $F(t) = Y_0 + U_0 \cdot t + R(t)$ that describes the position of the frontal and back points of a growing spherical bubble (the boiling point corresponds to coordinate $Y_0$, $R(t)$ is a change in the bubble radius), floating at constant velocity $U_0 = 0.24$ m/s, is also shown in this figure. It can be seen that up to 20 ms, the experimental data are in a good agreement with the calculated dependence $F(t)$. Then, due to a change in the bubble shape the experimental data do not coincide with dependence $F(t)$. From moment $t = 70$ ms, back point $B_b$ begins approaching the frontal point $A_b$ with acceleration $A = 10$ m/s$^2$, resulting in formation of a vapor cavity of the “oblate ellipsoidal cap” type.
Figure 4. Change in the shape of the vapor bubble. Acetone, saturation pressure $P_s = 29.0$ kPa, overheating $\Delta T = 52$ K. (a) - curvature (radius) of the bubble; (b) - coordinates of points $A_b$, $B_b$, $C_b$.

For a system of two bubbles, dynamics of the second bubble depends on the mutual position of bubbles. When the distance between bubbles is greater than the diameter of the upper bubble, their mutual influence is insignificant. As the bubbles approach each other, the shape of the upper part of the lower bubble becomes conical (Figure 3a 58.3 ms), as well as in the pool environment (Figure 3b, 80 ms). The shape of the upper bubble depends little on the position of the lower bubble until the moment of their collision, but after the collision it can transform significantly. Figure 5 shows the data for the movement of singular points on the vapor cavity for the case, where the second bubble is formed near the stern portion of the upper bubble, whose shape at this point is hemispherical. In this case, we can note several features that are characteristic of interaction of two bubbles: various dependencies for moving upper $C_b$ and lower $D_b$ parts of the second bubble. Within 5 ms, point $C_b$ moves at a constant speed of 1 m/s, point $D_b$ moves, as well as a single bubble. After the collision of bubbles, a cone-shaped convexity $E_b$ is formed in the upper part of the first bubble. The velocity of point $E_b$ is constant and its value is two times higher than the rise velocity, but less than the velocity of point $C_b$. Point $D_b$ approaches the stern part of the upper bubble with acceleration $A = 100$ m/s$^2$, and its apparent motion merges with the motion of point $B_b$ at a constant velocity equal to the rise velocity of 0.2 m/s. The vapor cavity as a whole acquires a bell-like shape. Thus it is seen that after coalescence of bubbles, the vapor movement in the cavity is very heterogeneous. The constant velocity of motion of point $C_b$ and large values of acceleration during the motion of point $D_b$ indicate that the fields of pressure and velocities behind the upper bubble, and effects associated with the changes in the surface energy upon combining bubbles play a significant role in the investigated processes.

As the number of interacting bubbles increases, the steam structures of complex shape arise, whose evolution depends on many parameters. For example, Figure 6 shows how the shape of the vapor cavity changes with interaction of three spherical bubbles ($a$, $b$, $c$). Bubble $a$ transforms successively into a spherical segment, a torus, two separate bubbles, one of which is detached from the vapor cavity. Bubble $b$ takes a conical shape, and after its coalescence with bubble $c$, the vapor cavity takes a "mushroom" and spherical shape.
Figure 5. Change in the shape of vapour cavity. Acetone, saturation pressure $P_s = 29.5$ kPa, overheating $\Delta T = 41$ K. (a) - video frames and location of special points $A_b$, $B_b$, $C_b$, $D_b$ in the vapour space; (b) - change in the position of singular points of $Y$ in time $t$.

Figure 6. Change in the shape of the vapor cavity, when three steam bubbles interact. Acetone, saturation pressure $P_s = 29.5$ kPa, overheating $\Delta T = 41$ K.

4. Conclusions
Floating up and growth of a single vapor bubble in acetone was studied experimentally, and interaction between the emerging vapor bubbles was considered. Experiments have shown that the pressure and velocity fields behind a pop-up vapor bubble have a strong effect on the growth dynamics.
of another vapor bubble located below. This effect is determined by the distance between the bubbles and growth phase of the first bubble at the moment of second bubble generation. When two bubbles merge, high values of acceleration in the motion of individual sections of the vapor bubble interface (up to 100 m/s²) are observed, while for the growth of a single vapor bubble, there are the order smaller values of acceleration in the motion of individual sections of the bubble interface (up to 10 m/s²). The nature of the shape change, when the upper bubble merges with the lower bubble, indicates that vapor spreading from the lower bubble into the cavity occurs in the form of a jet; as a result, conical perturbations are formed on the opposite side of the upper bubble. With an increase in the number of interacting bubbles, the number of combinations of the determining parameters (distance between the bubbles, bubble growth phase) increases sharply, and this makes it difficult to classify the resulting vapor structures.

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