Studying of the characteristics of a single bubble under subcooled liquid boiling

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Abstract. An experimental study of the characteristics of single (solitary) bubbles obtained by means of focused laser heating of the surface during the boiling of two subcooled liquids with significantly different properties: water and refrigerant R113 has been carried out. To obtain the most complete detailed information, the technique of synchronized high-speed video filming of the process in two mutually perpendicular planes with a frame rate of up to 150 kHz was used. It is shown that during the boiling of a subcooled liquid, the main mechanism of heat removal from the bubble dome into the surrounding liquid is an unsteady heat conductance. Differences in the behavior of solitary vapor bubbles in the case of boiling of two liquids (water and refrigerant R113) are shown.

1. Introduction

Due to the ability to remove extremely high heat flux densities at high heat transfer coefficients, subcooled liquid boiling is considered as an effective technology for cooling devices operating in extreme thermal conditions (nuclear power engineering, metallurgy, power electronics, and several other areas of modern industry).

To develop reliable methods for predicting cooling systems based on subcooled liquid boiling, it is necessary to have a complete mathematical description of the process, which is currently absent. To some extent, the lack of a rigorous description is compensated by a large amount of experimental data and the development of phenomenological models, among which the Snyder-Bergles model seems to be the most correct and effective. According to the model vapor bubbles function as a kind of micro heat pipes - in the contact zone of three phases near the boundary of a dry spot intensive evaporation of liquid occurs, and vapor condensation on most of the bubble surface (dome) takes place [1, 2]. This model also requires some refining and correction both regarding quantitative characteristics (for example, the evolution of the shape and size of bubbles in time) and a qualitative description of the phenomenon (the pattern of bubble “collapse”, the mechanism of heat removal from the bubble, etc.) [3].

In this work, using high-speed video filming of the process (up to 150 kHz), an experimental study of the characteristics of single (solitary) bubbles during the boiling of two subcooled liquids with different properties: water and refrigerant R113 was conducted.
2. Experimental setup
The studies were carried out on a setup, the main elements of which are shown in figure 1. The experimental setup was a closed circulation loop with a test section of rectangular cross-section 21 mm wide, 5 mm high, and 70 mm long (I in figure 1). As a heating surface, a Kh18N10T stainless steel plate with a diameter of 13 mm and a thickness of 0.1 mm, which was glued to the outer wall of the test section body was used. The plate was heated by a laser beam focused on an area up to 1–2 mm in diameter. A JOLD-100-CPXF-2P laser diode (Jenoptik company) (4 in figure 1) with a maximum power output of 100 W was used as a source of laser radiation. The laser radiation power was controlled by means of a pump current using a diode power supply. To increase the degree of absorption of laser radiation, an aerosol Graphite 33 was deposited on the outer surface of the plate with the measured emissivity at the laser wavelength equal to 0.92. A more detailed description of the other elements of the experimental setup can be seen in [4, 5].

Figure 1. The main elements of the experimental setup: 1 – test section; 2 – Phantom VEO 410s video camera; 3 – Photron Fastcam SA4 video camera; 4 – laser diode with a free lens focusing system; 5 – thermovisor.

To obtain the most complete and detailed information of the dynamics and characteristics of a solitary bubble under subcooled liquid boiling, a synchronized high-speed video filming system in two mutually perpendicular directions (along and normal to the heating surface) (figure 2) was developed. The synchronization circuit was assembled on TTL elements and a G5-54 generator with an adjustable pulse delay. Two video cameras Photron Fastcam SA4 (3 in figure 1) and Phantom VEO 410s (2 in figure 1) were used for filming. The use of the Phantom VEO 410s camera made it possible to increase the filming speed to 150 kHz, and to reduce the exposure time to 1 μs (the full cycle from the appearance to the collapse of the water bubble takes fractions of a ms). A dimension of the irradiated spot and a temperature distribution over its surface were determined using SDS Hotfind-D thermovisor (5 in figure 1). Figure 3a shows an example of such a distribution. The same temperature
distribution is shown in figure 3b in the graphic form. On this basis heat outflow rates from the irradiated spot were assessed. In most tests they were not more than 15%.

**Figure 2.** Frames of video filming of a solitary vapor bubble. Frame size: 1.9 x 1.9 mm. (a) - View along the normal to the heating surface (in front); filming with a Photron Fastcam SA4 camera, (b) - view parallel to the heating surface (in profile); filming with a Phantom VEO 410s camera.

**Figure 3.** Temperature distribution of the rear surface of the heating plate ((b) - over the diameter). Frame size (a): 14 x 18 mm.

The experiments were carried out at atmospheric pressure at mass flow rate $\rho_w = 0–300 \text{ kg/(m}^2\text{·s)}$, in the subcooling range $\Delta t_{\text{sub}} = 40–70°C$ for water and $\Delta t_{\text{sub}} = 20–40°C$ for refrigerant R113, respectively.

### 3. Results

As a result of the experiments, it was found that the duration of the bubble growth period for water is 100–150 µs. During this time, the bubble reaches its maximum size - 400–700 µm. That is, the initial period of the bubble's life is explosive nature. This leads to the formation of an evaporating wedge-shaped microlayer of liquid at the base of the bubble, due to which the process of intense evaporation takes place. For the entire subsequent period of its life, the vapor bubble (at $q$ from the wall far enough from the critical heat flux) decreases in size. That is, the amount of steam (heat) removed from the
bubble exceeds the supplied one. According to balance estimates, during the lifetime of a bubble, a volume of vapor passes through it, which many times (up to 10–30 times) exceeds the volume of the bubble itself. To remove a large amount of heat released by the vapor condensing on the bubble dome surface, a corresponding high-intensity heat transfer process must occur. Comparison of the typical Kolmogorov time scale of turbulence (~ 1–2 ms) and the lifetime of a vapor bubble (0.4–0.6 ms), which is typical for the considered situation, suggests that it is not the convection of the liquid flowing around the bubble, but unsteady heat conductance to the volume of cold liquid. The same idea is suggested by the formations of elevated temperature clusters ("thermics") formed in a liquid layer as a result of the collapse of vapor bubbles. Further research may help to detail this issue.

Due to the large surface area, the removal of vapor by condensation exceeds the flow of vapor as a result of evaporation of the microlayer, and after a fraction of a ms, during which the bubble decreases in size, it departs from the heating surface and collapses (figure 4).

![Figure 4](image_url)

**Figure 4.** Reducing the size of the bubble (collapse stage). Interval between frames - 73.3 μs, exposure - 6.7 μs: water subcooling $\Delta t_{sub} = 40^\circ$C; $\rho_w = 300$ kg/(m$^2$·s); $q = 1$ MW/m$^2$. Frame size is 1.9 x 1.9 mm.

In the case of boiling on a solitary nucleation site of subcooled refrigerant R113, which significantly differs from water in properties (table 1), the following typical pattern was observed (figure 5). In about 10 ms, the bubble grew up to 400–450 µm in diameter, detached from the nucleation site and, in the process of moving in the liquid flow (within the limits of the filming field), decreased in size to about 200–250 µm in 60–70 ms. The less intense condensation process of R113 vapor in comparison with water is associated with its worse thermophysical properties and lower subcooling. The shape of R113 vapor bubbles, when being located at the nucleation site, was much more similar to the spherical one than that of steam bubbles. Most likely that these significant differences in the times of processes and in the bubble shape from the case with water boiling are associated with the higher reduced pressure $p/p_{cr}$ values ($p_{cr}$ is the critical pressure) (table 2).
The results obtained are subject to further more detailed study and interpretation, which will require additional experimental research.

Figure 5. Reducing the size of the bubbles of R113 refrigerant vapor: $\Delta t_{\text{sub}} = 21.5^\circ\text{C}$, $q = 0.1 \text{ MW/m}^2$; $\rho w = 300 \text{ kg/(m}^2\cdot\text{s})$. Filming in profile, the movement of the liquid from left to right. Frame size: 0.66 x 3.6 mm.

Table 1. Properties of water and refrigerant R-113 in atmospheric conditions.

|                      | Water | Refrigerant R113 |
|----------------------|-------|------------------|
| Evaporating temperature, °C | 100   | 47.5             |
| Heat of vaporization, kJ/kg  | 2257  | 148              |
| Density of liquid, kg/m$^3$   | 998   | 1525             |
| Density of saturated steam, kg/m$^3$ | 0.6   | 6.3              |
| Thermal conductivity, W/(m·K) | 0.599 | 0.065            |
| Specific heat, J/(kg·K)       | 4183  | 984              |
| Dynamic viscosity, Pa·s        | $1\cdot10^{-3}$ | $0.53\cdot10^{-3}$ |
| Surface tension, N/m           | $7.27\cdot10^{-2}$ | $1.66\cdot10^{-2}$ |

Table 2. Critical parameters of water and refrigerant R113.

|                      | Water | Refrigerant R113 |
|----------------------|-------|------------------|
| Temperature, °C       | 374   | 214              |
| Pressure, MPa         | 22.06 | 3.4              |
| Density, kg/m$^3$     | 322   | 574.5            |

4. Conclusions
Using the technique of synchronized high-speed video filming of the process in two mutually perpendicular planes, data were obtained on the characteristics of solitary bubbles formed due to focused laser heating of the surface during the boiling of two subcooled liquids: water and refrigerant R113. It is shown that during the boiling of a subcooled liquid, the main mechanism of heat removal from the bubble dome into the surrounding liquid is an unsteady heat conductance. Differences in the behavior of solitary vapor bubbles in the case of boiling of two liquids (water and refrigerant R113) are shown.
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