Dynamics of bubble growth under a heated substrate

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Abstract. This paper investigates the growth dynamics of a vapor-gas bubble pressed against a heating plate by the buoyancy force. The shadow method was used to capture images, which were then automatically processed to calculate the size of the bubble. As expected, the bubble dynamics significantly depends on the heating power. It was found that the ratio of bubble diameter to bubble height increases as it grows.

1. Introduction
The transition from the liquid to the gas phase is one of the most widespread processes both in nature and in technology. During boiling and evaporation, a significant amount of heat is removed, which is required for the phase transition. Many cooling systems are based on this principle. During boiling and evaporation, many phenomena occur, whose understanding is key to creating modern two-phase systems. For example, thin liquid films that are promising for evaporative systems are prone to rupture [1-11]. Boiling also produces dry spots, contact lines, and microlayers located under the vapor bubble. Papers [12-16] showed the presence of intense evaporation in the microregion of the contact line, which is explained by the small thickness of the liquid film. In this case, the local heat fluxes in the area of the contact line can significantly exceed the average heat fluxes, thereby making a significant contribution to the total heat transfer.

The boiling process is mainly studied when vapor bubbles are detached from the heated surface under the action of a buoyant force [17, 18]. The boiling process on downward-facing surfaces is also studied, where the buoyancy force presses the bubbles to the substrate [19]. In [20, 21], thermocapillary convection around a single air or vapor bubble under the substrate was investigated.

In the present work, we experimentally investigate the evaporation process of a vapor-gas bubble under a transparent heated substrate. This technique is also promising for studying the dynamics and heat transfer in the meniscus of a liquid formed by an optically transparent substrate and a bubble pressed against it by the buoyancy force. The proposed method will allow carrying out high-precision thermal measurements together with optical methods with high spatial and temporal resolution in well-controlled conditions.
2. **Experimental equipment and methods**

The test section (figure 1) is a closed rectangular transparent plexiglass tank filled with a working fluid (ethanol). The top wall is a 2 mm thick sapphire plate, on the inner side of which a transparent ITO heater (8 mm × 80 mm) is deposited, which is connected to a power source. A copper tube is installed in the tank, through which water of a given temperature is pumped by a thermostat. To generate a bubble, a metal needle is used through which air is supplied with a syringe pump. The test section is installed on the goniometer for positioning relative to the horizon. To compensate for the expansion of the bubble during evaporation of the liquid, the test section is connected to another reservoir (not shown in figures 1, 2) with a constant level of the working liquid. The dynamics of the bubble under the heated substrate is visualized using the optical shadowgraph technique (figure 2), whose principle is as follows: light from the source passes through the collimating lens and is directed to the camera lens, the bubble blocks the path of the light, as a result of which its shape is visualized on the image. Images are captured using a camera with a shooting speed of 24 frames per second and a spatial resolution of 30 µm/pxl.

![Figure 1. Test section.](image1)

![Figure 2. Shadowgraph technique](image2)

3. **Results and discussion**

Figure 3 shows a series of shadow images of a growing gas bubble under a heated substrate. The upper dark stripe in the images is the substrate and the lower – copper tube. The bubble is created with a needle sometime after turning on the heating. The time is indicated from the moment the air bubble floats to the substrate. As a rule, from one to two bubbles emerge from the needle, which merge into a single bubble, while the initial volume of the resulting bubble under the substrate varies from 2 to 8 mm³. Further, the bubble begins to grow due to the evaporation of the liquid, and accordingly, the
composition of the gas phase inside it changes. It can be seen that after some time, other vapor bubbles also form under the substrate. These vapor bubbles can merge both with each other and with the main vapor-gas bubble.

![Figure 3. Dynamics of a vapor-gas bubble under a heated substrate](image)

The bubble volume was determined automatically using image processing. At the first stage, a filter is applied to the shadow image to increase contrast. Then, the median filter is applied to suppress the noise. Next, the image is binarized and closed contours are highlighted. It should be noted that in the raw image the part associated with the substrate is cut off to highlight a closed contour. To determine the volume, it is assumed that the bubble is symmetric around the vertical axis. Thus, the volume was calculated as the volume of the rotation body.

Figure 4 shows the bubble volume dynamics for different heating power. One can see that with increasing heating power, the bubble growth rate increases significantly.

![Figure 4. Bubble volume dynamics for different heating power](image)
Also, using image processing of the bubble growth, its height ($h$) relative to the substrate was determined, as well as its diameter ($d$) at the widest point (figure 5).

![Figure 5. Height (h) and diameter (d) of the bubble during its growth at a heating power of 3.68 W](image)

One can see that as the bubble grows, its height grows slower than its diameter, and accordingly the ratio of diameter to height increases. This effect is most likely explained by the pressing of the bubble to the substrate by the buoyancy force, which makes its shape more flattened.

4. Conclusion
The growth dynamics of a vapor-gas bubble under a sapphire substrate, on which an ITO film heater is deposited, has been studied experimentally. The rate of increase in the bubble volume strongly depends on the heating power. It was revealed that due to the buoyancy force, which increased as the bubble grew, the bubble diameter increased faster than the bubble height.

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