Features of heat transfer and phase-change on a pinned surface at pulse heat release

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Abstract. An experimental study was conducted of the boiling characteristics of water subcooled to the saturation temperature during pulsed heating on a smooth surface with a technical roughness of up to 5 μm and on a modified surface with cylindrical pins 200 μm in height and diameter, located at the nodes of a rectangular grid with a step of 400 μm, with an upward flow with a pressure of 0.29 MPa and an average flow velocity of 0.52 m/s. It was found that at an initial water temperature of 110°C for a modified surface, the rate of increase in the heater temperature is lower, and the onset time of nucleation is the same as for a smooth surface. For an initial water temperature of 80°C and an average temperature increase rate of about 5000 K/s, it was experimentally shown that the bubbles on the modified surface are larger, but their number and the share of the area occupied by them are significantly lower than on a smooth surface.

1 Introduction

Surface roughness, as well as the presence of artificially applied texture in the form of ribs, pins or depressions, can have a significant effect on the appearance, growth and separation of vapor bubbles during boiling in a flow of subcooled liquid. In turn, the characteristics of nucleate boiling affect the heat transfer coefficient and the critical heat flux. In the classic work of Hsu [1] the mechanism of the influence of heating conditions on the range of activated nucleation centers is revealed. Sarker et al. [2] investigated the influence of surface roughness and wettability on the characteristics of nucleate boiling and showed that a decrease in wettability leads to an increase in bubble size. When compared to a rough surface, the smooth surface produced bubbles of smaller diameter and longer departure times. Zou et al. [3] showed that the use of microfins significantly increases the critical heat flux, compared to a smooth surface, due to the early evaporation of the microlayer. Mehta and Kandlikar [4] noted an increase in the heat transfer coefficient and critical heat flux when applying various grooves to horizontal and vertical cylindrical heated surfaces cooled with water at atmospheric pressure. In the work [4] High-speed video recording allowed us to establish the mechanism of bubble ejection by leaking water, which is most pronounced for deep V-grooves. Patil and Kandlikar [5] achieved improved heat transfer during boiling due to the

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mechanism of accelerated bubble separation from the fin tops due to liquid leakage from microgrooves. In this case, the preferential arrangement of bubbles on the fin tops was achieved by creating a hydrophilic microporous coating and polishing the bottom of the grooves. In this paper, the effect of cylindrical pins on heat transfer during water boiling on a vertical surface at different subcooling values and non-stationary heating with different released power was studied.

2 Experiment setup

The experiment was conducted using the equipment of the High-Temperature Circuit Multi-Access Research Center. The working section was a channel with a square cross-section and an internal size of 18 mm, inside which there was a heater made of 12X18N10T steel in the form of a cylinder 120 mm long with an external diameter of 12 mm and a wall thickness of 1 mm. Water with a temperature of 80°C and 110°C and an average velocity of 0.52 m/s was supplied from the bottom up at an absolute pressure in the channel of 0.29 MPa. The heater temperature increased from the flow temperature to 130–270°C in a short time (6–800 ms) due to the supply of an electric pulse through the heater. As the heater temperature increased, the heat exchange mode on its surface changed from convective through nucleate boiling to transitional. Two heaters were used in the experiment: one smooth with a technical roughness of up to 5 μm and the second modified using a laser. Laser processing was performed using the MiniMarker-2 system (OOO Laser Center) with a fiber nanosecond laser (IPG-Photonics) with a wavelength of 1064 nm. The focused beam diameter was 50 μm at a level of 1/e2. Using the laser-erosion processing method, pins with a diameter and height of 200 μm were formed, located at the nodes of a rectangular grid with a step of 400 μm. The temperature of the inner surface of the heater was measured using thermocouples. When conducting experiments with a channel filled with water, the thermocouple readings do not reach the maximum temperature of the heater due to the thermal inertia of the thermocouples and rapid cooling of the heater after the current is turned off. To estimate the required correction for the thermal inertia of the thermocouples, preliminary measurements were carried out on the same heat generation parameters in the absence of liquid in the channel. Vapor structures on the heater surface are recorded using a Phantom v2012 high-speed video camera with a spatial resolution of 5.5 μm per pixel. Filming was done at a frequency of 180,000 frames per second with a frame size of 256×256 pixels.

3 Results

A series of experiments were conducted with different heat release powers at an initial water temperature of T_0= 110°C, which corresponds to subcooling of 23 K, and the average rate of increase in heater temperature was determined. Comparison of the results in Fig. 1 for smooth and modified surfaces shows that for the same specific heat release powers, the rate of increase in heater temperature is lower for the modified surface.

Using video data, the time of appearance of the first bubble (τ_{ONB}) was determined for each experiment. Figure 2 shows a comparison of τ_{ONB} for smooth and modified surfaces at an initial water temperature of T_0 = 110°C. It can be seen that surface modification does not have a significant effect on the time of onset of nucleation.

Fig. 3 shows the results of processing video frames for the initial liquid temperature T0=80°C and the average heater temperature growth rate of about 5000 K/s. In 32 frames for the smooth heater and 34 frames for the modified heater, all bubbles were outlined, their number N and total area F_v were found depending on the time elapsed since the first bubble appeared. The density of nucleation centers and the fraction of the area occupied by vapor

were obtained by dividing the number of bubbles by the frame area F. For the modified surface, the ratio of the number of bubbles and their total area to the frame area minus the area of the pins, F_{np}, was also considered, since, according to the video recording data, bubbles do not form on the tops of the pins.

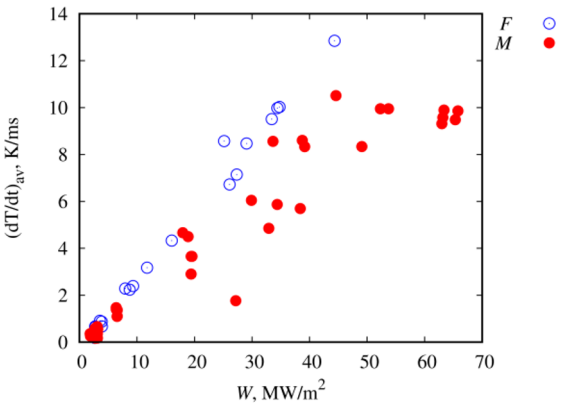

Fig. 1. Dependence of the average time rate of increase in the heater temperature on the released power. F – smooth surface, M – modified.

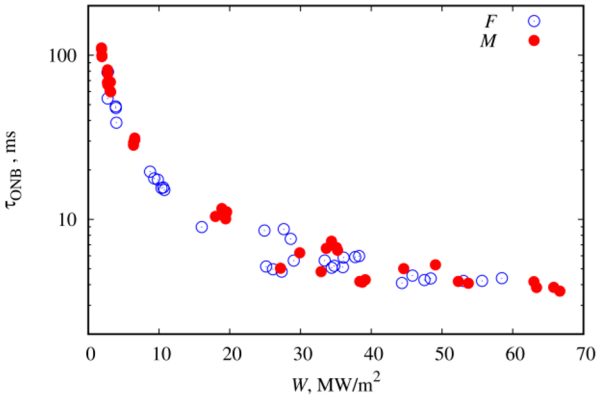

Fig. 2. Dependence of the time interval from the start of heating to the appearance of the first bubble on the power. F – smooth surface, M – modified.

For the values of N and F_v, referred to the total area F, correlations in the form of exponential trends were obtained, and the trend diameter of bubbles D_{trend} was calculated using the formula

$$D_{trend} = 2\left[\frac{1}{\pi}\left(\frac{F_v}{F}\right)_{trend} / \left(\frac{N}{F}\right)_{trend}\right]^{1/2} \quad (1)$$

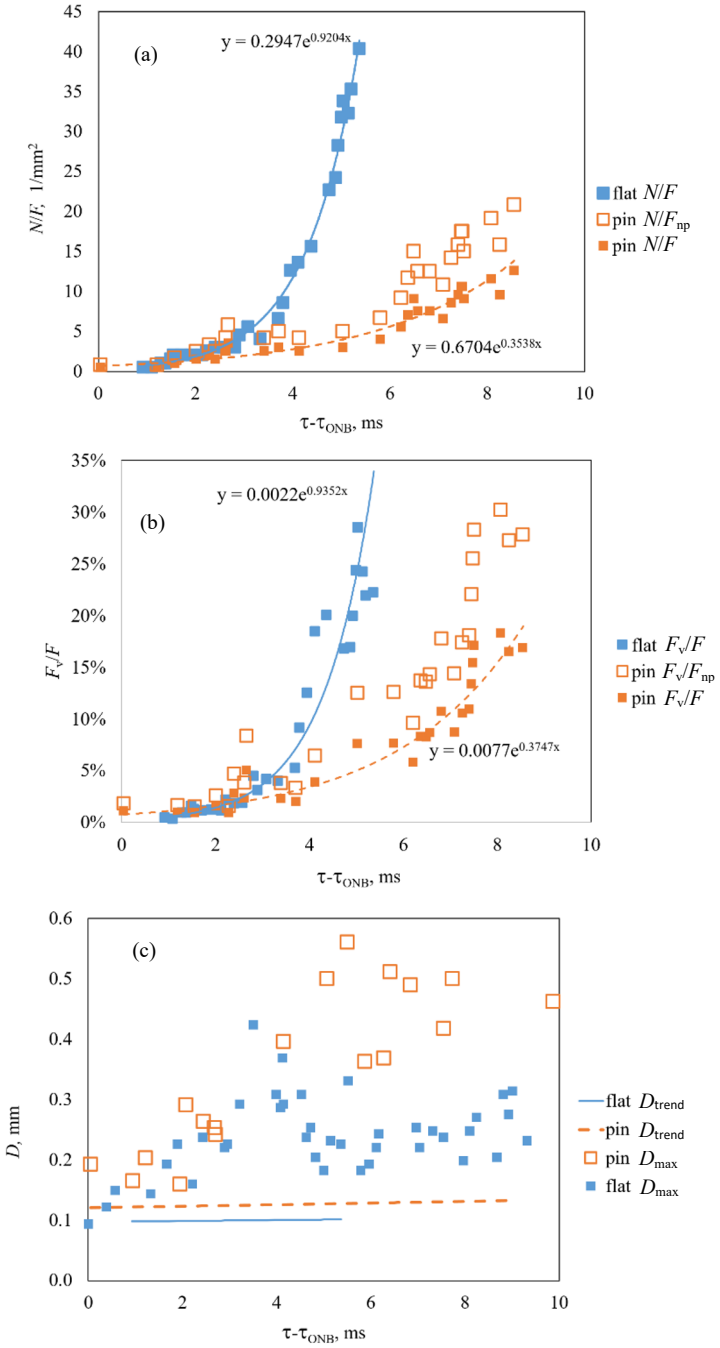

Fig. 3. Characteristics of nucleate boiling at T0=80°C and dT/dt=5000 K/s. (a) – density of nucleation centers, (b) – fraction of the heater surface area occupied by vapor, (c) – bubble diameter according to the trend and maximum diameters of the largest bubbles.

From Fig. 3 it can be concluded that during the first 4 ms after the onset of boiling on the smooth surface and on the modified surface the number of bubbles and the fraction of the

area occupied by vapor grow with approximately equal intensity. In the subsequent period of time on the smooth surface the growth of the density of nucleation centers sharply accelerates and the smooth surface begins to significantly outpace the modified one both in the density of nucleation centers and in the fraction of the surface occupied by vapor. In Fig. 3 c, in addition to the lines representing the graph of the D_{trend} function, there are also markers indicating the maximum diameter achieved by the largest bubbles at the moments of time corresponding to the values along the horizontal axis. It should be noted that on the modified surface the bubbles are larger than on the smooth surface, which is apparently caused by the larger values of the thickness of the superheated layer in the space between the pins on the modified surface, compared to the smooth surface.

4 Conclusions

An experimental study of non-stationary nucleate boiling in a flow of water subcooled to the saturation temperature was conducted for a smooth surface and for a modified surface with laser-formed pins. The following quantities were measured: heater temperature rise rate, nucleation onset time, dynamics of change in nucleation center density and fraction of area occupied by vapor, and bubble sizes. It was found that at water flow subcooling of 23 K and released power from 1 to 70 MW/m2, the time periods from the start of heating to appearance of the first bubble for both surfaces coincide, but the average rate of heater temperature rise over the entire heating time is lower for the modified surface. For flow subcooling of 53 K and an average rate of temperature rise of 5000 K/s, it was shown that, per unit surface area free of pins, the nucleation center density and the fraction of surface occupied by vapor coincide during the first 4 ms of boiling for the smooth and modified surfaces. Subsequently, the growth of both quantities sharply accelerates for the smooth surface. At the same time, on the modified surface all bubbles become significantly larger than on the smooth surface. Thus, an increase in the efficiency of heat transfer during bubble and transition boiling is observed due to the formation of cylindrical pins on the surface of the heater.

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