Boiling of liquid in a mini channel on smooth, rough and porous surfaces.

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Abstract. A series of experiments were conducted to study the effect of the heater coating on the frequency of formation of steam bubbles and on heat exchange during boiling in the channel. Three different surfaces were used: 1) smooth, 2) rough and 3) porous. It was found that at relatively low heat fluxes, the specific frequency of bubble formation on a rough surface is higher than on a smooth one. However, with an increase in the heat flux, the difference in the frequency of bubble formation on rough and smooth surfaces practically disappears. At the same time, bubble formation on a porous surface occurs with almost 3 times the frequency, compared to both smooth and rough in the entire range of heat fluxes (up to 500 W/cm^2). The obtained results can explain the recorded fact of a significant increase in the heat transfer coefficient and the critical heat flux on a porous surface.

1 Introduction

Boiling is one of the most efficient and simple ways to remove large amounts of heat. This process has been well studied [1], and flow boiling in channels is currently being actively studied [2].

The study of flow boiling in microchannels is especially relevant for cooling electronic and microelectronic equipment. Semiconductor industry specialists at the international level note the problem of cooling microelectronic devices at high and ultra-high heat flows with uneven heat release [3]. In addition, the authors' team previously obtained results on two-phase flows in a channel, boiling and bubble formation [4-6].

The integral heat flow on a chip can exceed 100 W/cm^2, and the local heat flow in individual areas ranging in size from 0.1 to 2 mm, the so-called "hot spots", can be more than 1 kW/cm^2 and vary both in space and time. This problem is one of the main obstacles to the creation of a new generation of high-performance processors with 3D integration.

The aim of the study is to analyze the dynamics of bubbles and heat exchange during boiling in mini- and microchannels on a smooth, rough and porous surface. The case of uneven heat release and different underheating of the working fluid is considered.

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2 Experimental setup and materials

The experiments were carried out on a work site equipped with a heater measuring 10x10 mm² and having a thermal power of 3.5 kW. The assembled working section is shown in the photo (Figure 1), and the sectional diagram of working section is shown in Figure 2.

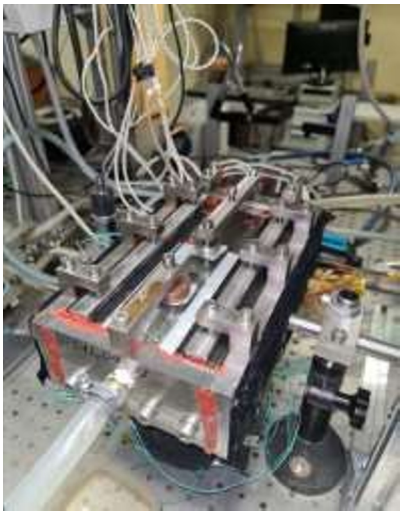


Fig. 1. Photograph of an experimental setup with a thermal power of up to 3.5 kW.

The upper wall of the channel consists of 15 mm thick clear glass, which allows for visualization of the hydrodynamics of the boiling process. The lower part of the channel is a stainless steel plate into which a copper rod with a 1x1 cm^2 head is pressed, acting as a heater. The uniformity of the height was controlled by a Micro-Epsilon IFC2451 confocal sensor.

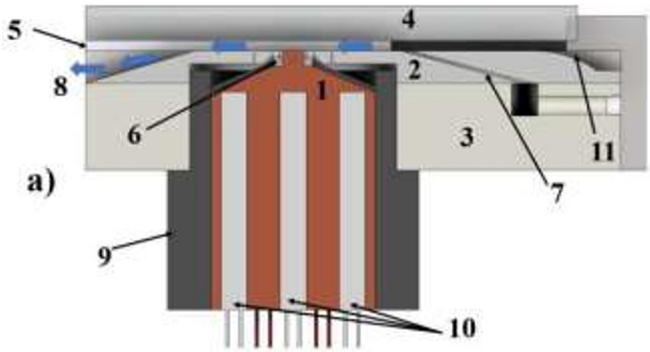


Fig. 2. Working section with a 10x10 mm^2 heater in longitudinal section. 1 – Copper heater, 2 – stainless steel plate, 3 – TECAPEEK base, 4 – glass top cover, 5 – fluoroplastic insert, 6 – paronite gasket, 7 – liquid inlet nozzle, 8 – outlet nozzle, 9 – aerogel thermal insulation 10 – cartridge heaters, 11 – gas inlet.

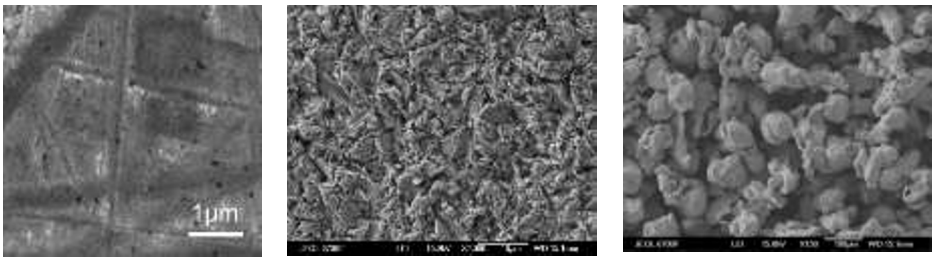
Using 6 thermocouples, 0.25 mm in diameter, embedded in the heater, and 9 thermocouples, 0.5 mm in diameter, embedded in the steel plate, the heat flow in the copper rod, as well as thermal leaks into the stainless steel plate, are determined. To further minimize radiation heat loss, the copper heater was nickel-plated on the outside. The heat source is 7

cartridge heaters with a thermal power of 500 W. Thermal contact between the cartridge heaters and copper is provided by a thin layer of liquid metal thermal interface based on a gallium alloy. The copper heater block is wrapped in aerogel sheets with a thermal conductivity of 0.019 W/(m K) at room temperature, which significantly reduces heat loss to the atmosphere. The heat flow from the heater is defined as the heat flow along the copper rod, measured using thermocouples, minus thermal leaks into the plate.

The working fluid is supplied to the working section through a circuit consisting of a pump, a plate heat exchanger for thermal stabilization of the working fluid using a thermostat, and an ultrasonic flow meter. The temperature of the liquid at the inlet to the working section is controlled with an accuracy of ± 1 °C. The temperature of subcooling of water to the saturation temperature was about 75 °C. When conducting experiments with a heating power of more than 200 W, an auxiliary circuit is used to cool the working fluid. The pressure at the inlet and outlet to the channel was measured by pressure sensors. Pure Milli-Q water was used as the working fluid.

Visualization was performed using a high-speed FASTCAM SA 5 camera. The shooting speed in the experiments reached 775,000 frames per second. The camera is equipped with a high-spatial-resolution optical system, in particular Mitutoyo M PLAN APO x5 and x10 lenses, which allow achieving a spatial resolution of about 1 μm per camera pixel.

In the experimental studies, three types of substrates were used: a smooth copper substrate, a rough copper substrate and a copper substrate coated with a porous layer. The surface morphology of the studied samples was studied by scanning electron microscopy (SEM) on a Jeol JSM 6700F (Jeol, Japan) in the secondary electron mode at an accelerating voltage of 15 kV and magnifications up to 20,000x. A micrograph of a smooth copper substrate obtained by scanning is shown in Figure 3a. It can be seen that the surface is quite smooth and has traces of grooves from mechanical polishing.



(a) (b) (c)

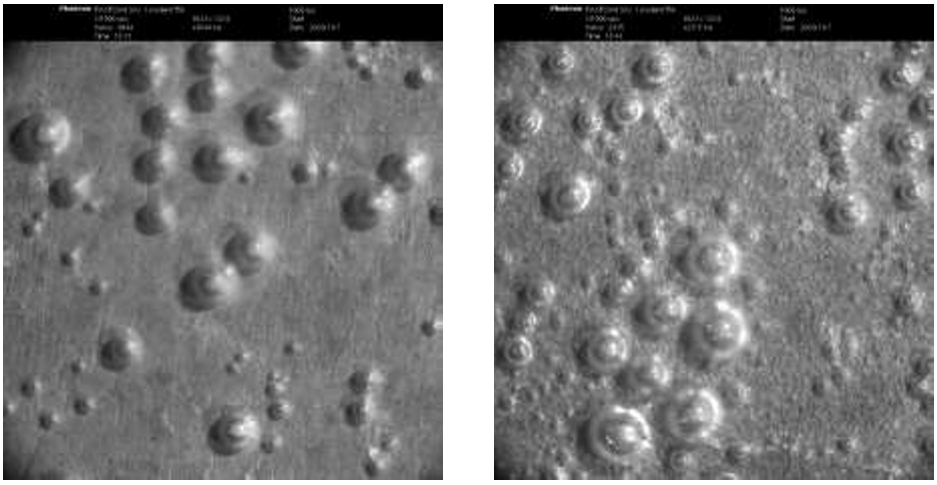
Fig. 3. Surface morphology of substrates obtained by scanning electron microscopy (SEM) Jeol JSM 6700F: a) copper substrate; b) rough copper; c) porous coating.

The rough surface (Figure 3b) was produced by abrasive processing of a smooth copper substrate, with the mean square surface roughness being about 0.5 μm (as measured by atomic force microscopy).

The porous surface was produced by applying nickel powder (particle size of about 50 μm) to a copper base with subsequent sintering by electric current discharge. The formed porous nickel coating had a thickness of about 200 μm. An example of an image of the porous coating obtained by an electron microscope is shown in Figure 3c. The coating withstands several heating-boiling-cooling cycles without significant changes in its properties in terms of heat exchange.

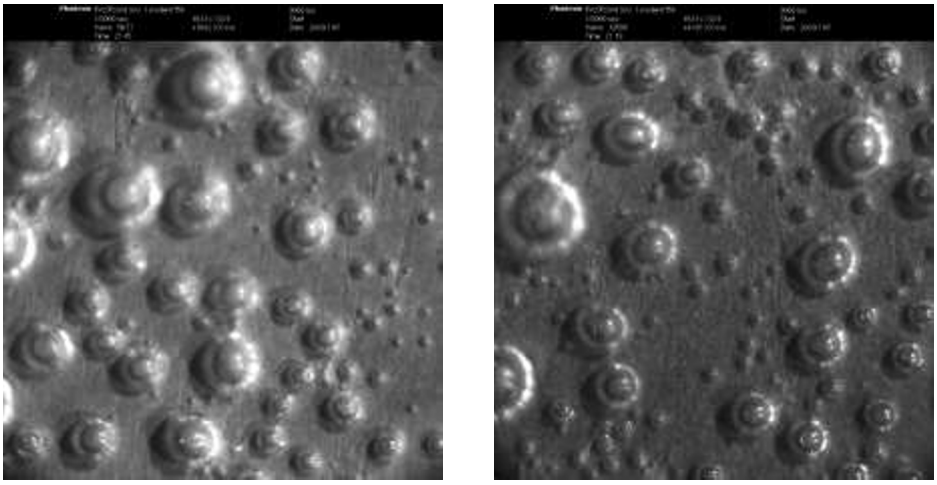
3 Results

A series of experiments were conducted to study the effect of the heater coating on the frequency of formation of steam bubbles. Three different surfaces were used: 1) smooth, 2) rough and 3) porous. Figures 4-6 show typical photographs of boiling on smooth, rough and porous surfaces, respectively.



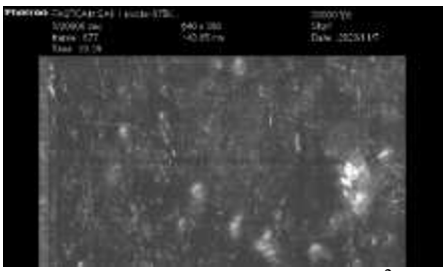
(a) (b)

Fig. 4. Photos of boiling water in a channel on a 1x1 cm^2 heater. The power on the heater is 140 W. (a) smooth surface, (b) rough surface. The frame size is 2.17 x 2.17 mm^2.

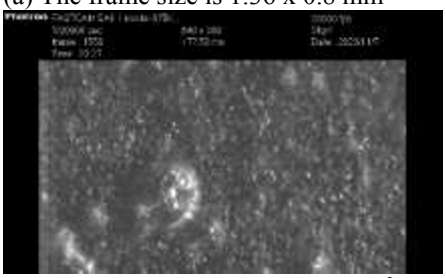


(a) (b)

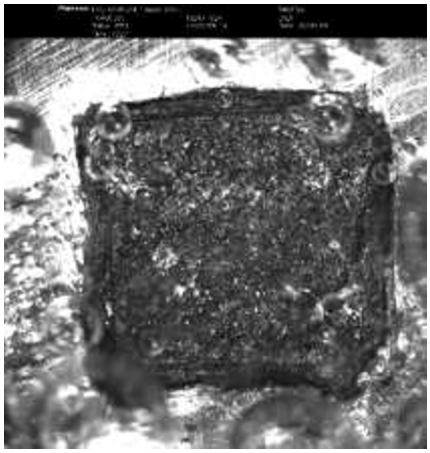
Fig. 5. Photos of boiling water in a channel on a 1x1 cm^2 heater. The power on the heater is 267 W. (a) smooth surface, (b) rough surface. The frame size is 2.17 x 2.17 mm^2.



(a) The frame size is 1.36 x 0.8 mm^2

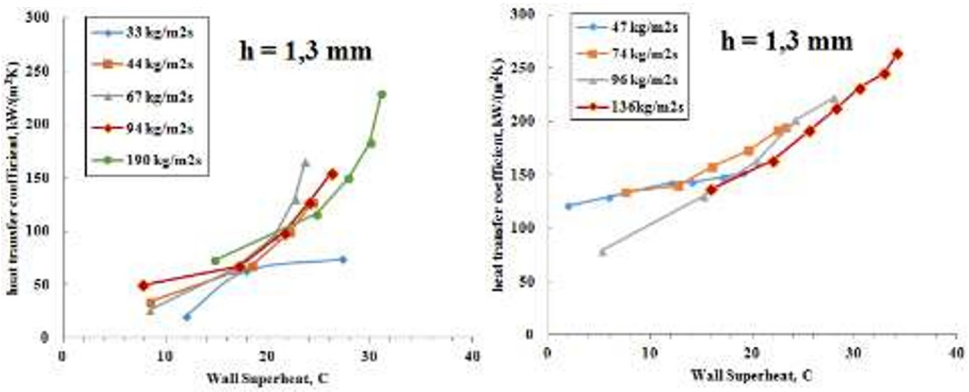


(b) The frame size is 1.36 x 0.8 mm^2



(c) The frame size is 4,24 x 4,24 mm^2

Fig. 6. Photos of boiling water in a channel on a 1x1 cm^2 heater (a and b) and on a 3x3 mm^2 heater (c). The power was 532 W and 505 W on a 1 x 1 cm^2 and 3 x 3 mm^2 heater, respectively. (a) smooth surface (b) rough surface (c) porous surface.



(a) (b)

Fig. 7. Heat transfer coefficient, depending on the wall superheating temperature, during boiling in a channel (channel width 30 mm, height 1.3 mm, 3 x 3 mm^2 heater) for different water flow rates. Heater surface: a) smooth, b) porous.

Figure 7 shows heat transfer coefficients, depending on the wall superheating temperature for different heater surfaces: a) smooth, b) porous. It is seen that the heat transfer coefficients for the porous surface are significantly (up to 2-3 times) higher than those for boiling on the smooth surface.

The data were analysed and processed using the ImageJ graphics software package, which allowed frame-by-frame counting of the number of newly formed bubbles. Figure 8 shows a graph of the dependence of the specific frequency of bubble formation on the heat flux on the heater.

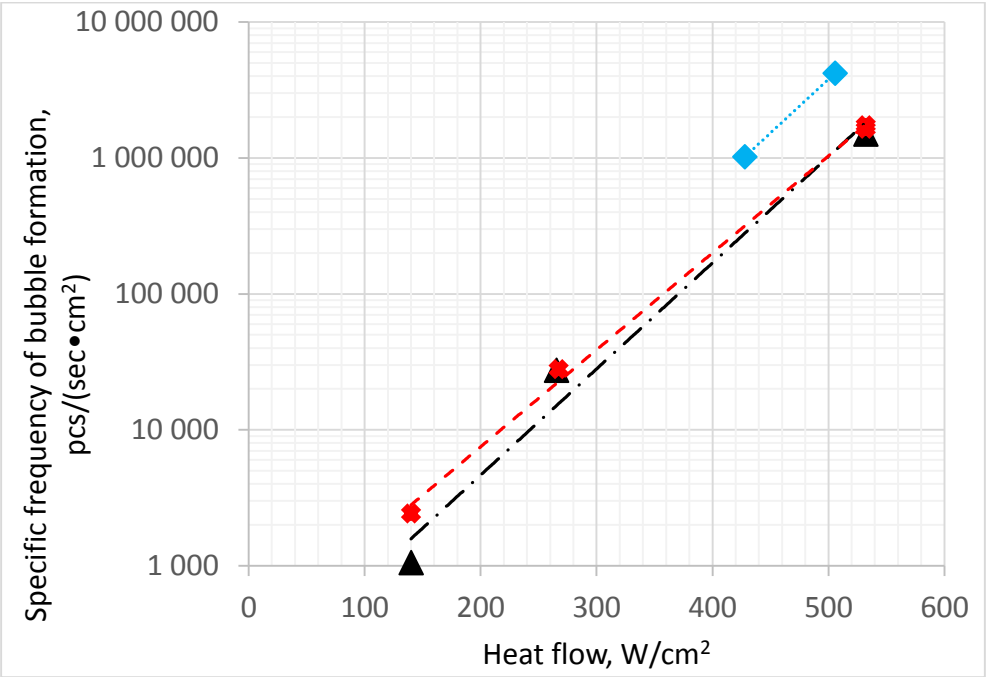


Fig. 8. Specific frequency of bubble formation (formation of new bubbles per 1 second from 1 cm2 of heater area) depending on heat flow. Legend: black points - smooth surface, red points - rough surface, blue points - porous surface. Trend lines are indicated by corresponding colours.

At the heat flux of 140 W/cm^2, the specific frequency of bubble formation on a rough surface is higher than on a smooth surface. However, with an increase in the heat flux, the difference in the frequency of bubble formation on rough and smooth surfaces practically disappears. In this case, the formation of bubbles on the porous surface occurs is almost 3 times the frequency (4,200,000 pcs/(sec•cm^2)), compared to both a smooth (1,500,679 pcs/(sec•cm^2)) and a rough (1,744,540 pcs/(sec•cm^2)) surface with a similar heat flux of about 500 W/cm^2. The obtained results can explain the above-described fact of a significant increase in the heat transfer coefficient and critical heat flux on a porous surface, compared to a smooth one.

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