Experimental study of heat transfer in two-phase flow regimes in rectangular microchannel

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Abstract. Existing cooling systems do not fulfil modern requirements for heat removal from high-heat dissipating sources in electronic and microelectronic equipment. When reducing the flat channel thickness, the ratio of the surface to the volume increases inversely to the minimal transverse size of the channel, resulting in high intensity of heat transfer in microsystems. Schlieren and infrared methods serve to determine the main characteristics of a two-phase flow. The characteristics of heat and mass transfer and regimes are studied at various values of the heat flux.

1. Introduction
The development of technologies for heat exchangers of micro- and nano-sizes shows that such systems are much more energy efficient than macro-systems with channel sizes of more than 1 mm [1]. Existing cooling systems do not fulfill modern requirements for heat removal from high-heat dissipating sources in electronic and microelectronic equipment. When reducing the flat channel thickness, the ratio of the surface to the volume increases inversely to the minimal transverse size of the channel, resulting in high intensity of heat transfer in microsystems [2]. Such systems are becoming more widespread in microelectronics, aerospace industry, transport and power engineering. The value of removed heat fluxes in such mini- and micro-heat exchangers can be 1000 W/cm² and higher [3]. In this regard, understanding hydrodynamics in mini- and microchannels, which ensure the most efficient heat and mass transfer processes, is important for a wide range of technical applications.

To analyze the possibility of creating such systems, it is necessary to have information about characteristics of a two-phase flow in the microchannels having short and wide cross section geometries [4]. Despite a significant number of publications, the number of studies in slit microchannels are limited.

Development of the studies on heat transfer during the flow in the flat mini- and micro-channels moves towards a decrease in their height. The M-shaped curve with two maxima, describing the dependence of heat transfer coefficient on void fraction, is known for boiling in the round and rectangular channels with the minimal transverse dimension of 0.5-3 mm [5-8]. The first peak of the M-shaped curve is associated with the beginning of developed boiling and formation of a bubble flow. The region of decreasing heat transfer coefficient is determined by formation of large bubbles, and at transition to the ring regime, the second peak appears. Heat transfer at boiling in a channel with the height of 184 mm was investigated in the work of Bar-Cohen and Holloway [9], where it was noted that the maximal heat transfer coefficient is reached in the range of vapor content from 0.8 to 0.9. In this range, the annular flow turns into the rivulet flow. Numerical studies of the effect of a shear gas flow on a two-phase flow are presented in [10, 11]. Recent works have shown that the gas flow has a
stabilizing effect on the liquid film, allowing the removal of heat fluxes of up to 1200 W/cm\(^2\) in a channel with the height of 1 mm at the separate flow of liquid and gas [12]. In [13], the effect of the flat channel height from 170 to 2000 μm on the critical heat flux value was investigated. It was determined that for the equal and relatively low gas flow rates, the higher critical heat fluxes can be obtained in the channels of a lower height. The main aim of this work is to study the heat transfer in two-phase flow regimes in a slit microchannel with a height of 50 μm. This type of channels is promising for use in space applications, as gravitational forces do not significantly affect the regimes of two-phase flow [14].

2. Experimental setup and measurement methods

The working section is made of two parallel optical glass plates with 10-mm thickness. The distance between the glass plates is set by two constantan gaskets with the thickness of 50 μm. The plane-parallel nature and thickness of the glass and gaskets are strictly controlled. In the lower plate, a nozzle is made at the angle of 11°; through this nozzle, liquid is supplied to the space between the plates by means of a high-precision syringe pump. The working section is assembled as follows: constantan gaskets are clamped between the glass plates with the help of U-shaped stainless steel holders. A nozzle for liquid is also mounted using constantan gaskets. The working section is sealed with a silicone sealant. The lengths of the inlet sections for liquid and gas are calculated from the condition of a stabilized and uniform flow at the inlet to the main microchannel. After the assembly, the microchannel height is measured at several points using the confocal DT IFC2451 system. For the study with infrared method, an insert for the sapphire window is made in the bottom plate. An ITO heater is coated onto a sapphire window, and the contact pads for soldering wires are brought to the opposite side of the sapphire window using silver coating. Thus, the heater is located inside the microchannel, and the power for heating is supplied from the outside. All conductive elements are coated with dielectric varnish for shielding from the microchannel body. The silver surfaces on the sapphire crystal are soldered using indium solder. These solders have good adhesion and do not

Figure 1. Scheme of experimental setup.
require high surface temperature (sapphire). Using the IR method and the ITO heater are well studied within the frameworks of pool boiling in [15-17].

The experimental setup is shown in Figure 1. Gas is supplied to the gas chamber of the microchannel (3) from the cylinder (1) through the high-precision Bronkhorst flow controller (2). FC-72 is used as a working liquid, and high-purity nitrogen is used as a working gas. A pressure sensor BD sensors (7) is installed in the gas chamber to measure the pressure at the channel inlet. Fluid is supplied from the reservoir (5) using a peristaltic pump (4). At the outlet of the microchannel, a pressure sensor BD sensors (8) is installed in the chamber (9). At the outlet of the microchannel, a heat exchanger is installed to condense the working liquid, which is cooled by a thermostat. Next, a separator is installed, and its internal volume is cooled; there condensed liquid is collected, which is then collected in the tank (12). Two pressure sensors are installed at the inlet to the channel and at the outlet. At the top of the microchannel, a system for visualization by the schlieren method is installed; it includes a light source (13), two lenses (14.16), a beamsplitter (15) and a digital camera with a macro lens. In the lower wall of the microchannel in the region of the heater (20), a system for imaging with a Titanium 570M infrared camera (18) is mounted; a silver mirror (19) is used in the system for visualization on the bottom side of the microchannel. The system registers infrared radiation in the wavelength range of 3.7-4.8 μm. Sapphire is transparent to infrared radiation by 85% (at the wavelength of 3.7 μm). The ITO heater is transparent in the visible range and opaque in the infrared spectrum. Radiation from the surface passes through the lens and it is received by the radiation-measuring instrument. An electrical signal coming from the radiation receiver is amplified by the amplifier and converted by an analog-to-digital converter. The digitized values are transferred to a personal computer. A synchronous technique that allows registration of liquid film deformations and heat flux values in time is developed.

![Figure 2. Characteristic image of a two-phase flow in a microchannel during heating.](image)

3. Calibration method
A series of experiments were carried out to measure the dependence of the resistance of the ITO heater. Heater resistance was measured using the Keysight agilent 34970A high-precision measuring system. The heater was placed in a specially designed stand in the KS 100-1 dry-block calibrator, which sets and maintains temperature with high accuracy using Peltier elements. For improved temperature uniformity, distilled water was poured inside the measuring vessel. Temperature measurements were carried out using a B7-99 high-precision thermometer at two points on different sides of the heater; thus, uniformity in temperature distribution was further controlled. The results of the study demonstrated that the conductivity of the heater was linearly dependent on temperature, but its resistance varied slightly. Therefore, high-precision systems such as the Keysight agilent 34970A were necessary for measurement. The next task was to calibrate the IR camera. For this, an experimental setup was assembled in which a liquid, Milli-Q water, circulated. The temperature of the liquid was set using a heat exchanger, which was connected using a liquid circuit to the thermostat. To control the temperature, two thermocouples were used at the inlet to the microchannel and at the
outlet. Using these thermocouples, temperature uniformity was also monitored. For better uniformity, the work site was insulated. The values were fixed only when the temperature difference was less than 0.5 degrees. During the experiment, the readings of both thermocouples, the values of the thermal imager, its own temperature, and also the resistance of the ITO heater were recorded. According to the testimony of the ITO heater resistance, a comparison was made with the results of its own calibration, which showed the validity of using the proposed methods. As a result of calibration experiments, 3 methods for measuring temperature were identified. The main method consisted of studying the temperature field using a thermal imager and the obtained own calibration. Auxiliary methods were temperature control using a calibrated heater and standard calibration for the thermal imager, taking into account the transmittance of sapphire. Temperature was also measured at the inlet and outlet of the channel.

4. Experimental results
After calibrated experiments, the adiabatic two-phase flow was investigated. The following flow patterns were detected: jet, bubble, churn, annular and stratified. A regime map was created based on the obtained data. Next, a study of the influence of heat flux on a two-phase flow in a microchannel was carried out. FC-72 was used as a liquid, and nitrogen was used as a gas. The studies were carried out at quite high gas flow rates $Q_g = 20 - 200$ ml/min and liquid flow rates $Q_l = 6 - 10$ ml/min, when the heater was permanently wetted. The heating power varied from 0 to 20 watts. Figure 2 shows a typical schlieren image of the two-phase flow during heating. The red square indicates the area of the heater. It is clearly seen how the void fraction increases as the flow passes through the heater. When a churn regime is formed in the initial region of the channel, then, as the flow passes through the heater, the regime is transformed into a stratified one due to evaporation. The pressure drop, temperatures, and flow patterns were studied at various values of the heat flux.

![Figure 3. Heat flux versus temperature difference.](image-url)
Figure 3 shows the data of the temperature difference between the heater and the liquid at the inlet of the microchannel versus the heat flux at the heater when $Q_l = 8$ ml/min; $Q_g = 20$ ml/min. The temperature at the heater was determined using the IR camera. The measurement results were processed in the Altair program, which was supplied with the IR camera. The data were averaged over the area of the heater, then the results of the calibration experiment were used to determine the temperature values. At the minimum values of the heat flux, the regime practically did not change, while at high values of the heat flux a significant amount of liquid evaporated, due to which the gas content increased significantly and the regime changed. In this case, the heater remained wet all the time, therefore, in Figure 3, a significant increase in the temperature difference with an increase in the heat flux was not observed. The dependence was close to linear approximation. Thus, the heat transfer coefficient was determined to be $5.2 \times 10^3$ W/m$^2$K.

There is a change in the size of liquid drops, which are vertical liquid bridges, which can be clearly seen in Figure 2. A detailed study of this regime under adiabatic conditions is presented in [18]. When heated, such liquid bridges evaporate, affecting heat transfer. Figure 4 shows the dependence of the average value of the equivalent diameter of the drops on the heat flux. The average equivalent drop diameter is determined from the equivalent diameter measurements for 90 different drops for each $q$ value. Equivalent diameter $D$ is calculated as follows $D = (a \cdot b)^{1/2}$, where $a$ and $b$ are semi-major and semi-minor axes of elliptical drop. The figure shows that with an increase in the heat flux, the average drop size decreases significantly. At heat fluxes of 6–10 W/cm$^2$, the average drop size is more than 1.5 times smaller than the drop size under adiabatic conditions. At higher values of the heat flux, the drops begin to completely evaporate as the heater passes.

![Figure 4](image_url)  
*Figure 4. Average equivalent drop diameter versus heat flux.*
Conclusion
The first experimental study of heat and mass transfer in a microchannel with a height of 50 μm and a width of 10 mm has been carried out. An ITO heater with a size of 10×10 mm² in direct contact with the working liquid was used as a heater to minimize thermal leakage. To study heat transfer, the IR method was used through a sapphire crystal on which the heater was sprayed, and the schlieren method was used to study hydrodynamics. Using complex methods, a series of experiments has been carried out to study heat transfer and hydrodynamics in a microchannel with heating. It is shown that liquid drops, being vertical liquid jumpers are formed in the flow. With an increase in the heat flux, the diameter of the drops decreases, and with a heat flux of more than 10 W/cm², the drops begin to completely evaporate.

Acknowledgments
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