Influence of superficial gas velocity on heat transfer in a two-phase system with additive heater surfaces

K S Eloyan\textsuperscript{1}, F V Ronshin\textsuperscript{1,2}, A A Litvintceva\textsuperscript{1} and V V Cheverda\textsuperscript{1,2}

\textsuperscript{1} Kutateladze Institute of Thermophysics SB RAS, 630090, Novosibirsk, Russia
\textsuperscript{2} Novosibirsk State University, 630090, Novosibirsk, Russia

E-mail: karapet8883@gmail.com

Abstract. The problem of removing high heat fluxes from a powerful microelectronic element (chip, microprocessor) is one of the most difficult tasks. One of the promising methods for cooling is the use of two-phase systems in a minichannel with a stratified flow regime. Additive technologies allowing the creation of structured surfaces are of increasing interest. The study of heat transfer using structures on the surface in the form of cylindrical protrusions in comparison with a smooth surface with characteristic size (diameter and height) equal to 300 µm is presented in this work.

1. Introduction
The problem of cooling the microelectronics components (chips, processors, transistors) with high heat generation on the surface is one important task in the field of applied thermal physics. One of the requirements of modern cooling systems is low power consumption. In modern data centers, more than 40% of all energy is consumed by the operation of cooling systems. In advanced solar concentric systems, there are problems of removing high heat fluxes (more than 500 W/cm\textsuperscript{2}) from photodiode components. [1]. There are several different methods for microelectronic cooling: 1) boiling in microchannels [2], 2) sprays [3], 3) micro-jets [4]. A new type of the efficient cooling system was presented, in which intense evaporation of liquid film, moving under the friction of gas flow in a flat micro- or mini-channel, is used to remove heat. The critical heat fluxes are compared for falling and liquid film shear driven by gas flow [5]. It is demonstrated that shear driven liquid is about five times more effective than falling liquid film.

One promising method of heat removal from the surface of highly stressed elements is evaporation of thin liquid films driven by concurrent gas flow. Various studies show the effectiveness of the application of two-phase systems, in which a stratified regime is created artificially. In the case of a stratified flow, high heat transfer coefficients are achieved at low-pressure drops, which is important in terms of technical implementation. It has been experimentally established that the critical heat flux for a gas-driven liquid film moving along a surface with a smooth heater can be several times higher that of a liquid film freely flowing down the surface for the same fluid flow rate [6, 7].

In [8], with the use of this method the heat flux as high as 1 kW/cm\textsuperscript{2} was removed from the heater with area of 10x10 mm\textsuperscript{2}, which is approx. 10 times higher than the critical heat flux in falling liquid films [9]. In [10-11] it was demonstrated that this system can stably operate at different channel heights (0.17 - 2.0 mm) and different inclination angles to horizon (0 - 360\degree).

To intensify heat transfer processes in a two-phase system with a layered flow regime, it is promising to use complex and intelligent surfaces. To increase the efficiency of heat dissipation, it is possible to
use highly developed surfaces with microstructures to intensify heat transfer processes due to the formation of menisci and increasing the contact line [12]. Currently, the area of additive production is expanding. Such highly developed surfaces can be created on the basis of additive technologies, since such a manufacturing technology opens up new possibilities in technical terms and has several advantages over traditional ones: the ability to create complex micro-scale structures, a shortened production cycle, the absence of defects in the sample due to growth from nanosized powders, and high strength products and manufacturing accuracy, a wide selection of materials for solving any problems (aircraft, automotive, medicine, heavy industry, etc.).

Additive technologies can be the key to the development and creation of new generation cooling systems with a complex structure and shape. Studies related to heat transfer during film flow with local heating and the use of microstructures are not enough to guarantee the effective functioning of such systems, which in turn inhibits the creation of affordable cooling systems for microelectronics with high heat generation.

This paper presents the research results of the heat transfer process of a two-phase system in a minichannel with a local heat source, which surface is produced using additive manufacturing technology.

2. Experimental setup

The scheme of experimental setup with an additive heater is shown in Fig. 1. The experimental setup is a system that has two working circuits: a closed liquid circuit and a gas circuit. The liquid circuit contains a pump for pumping water (LP): a constant flow pump gear pump (Ismatec Micropump with a Z-183 MI 0008 head). The gas mixture is supplied to the circuit from a dry N2 (G) cylinder. To control the gas flow rate, the Bronkhorst F-111AC-70K flow controller (CV) is used, which has a working range of gas flow rates from 0 to 100 liters/minute. At the outlet of the test section (TS), the gas-vapor mixture is condensed in a plate heat exchanger (C) ACH16-14H-F, a constant temperature is maintained along the second circuit of the heat exchanger due to the operation of the thermostat (T). After condensation, the liquid enters the tank, which begins to be pumped through the liquid circuit through the pump (LP). Dry N2 gas is used as the working gas phase; Milli-Q ultrapure distilled water is used as the working liquid.

![Figure 1. Schematic diagram of the experimental prototype of evaporative cooling system: TS – testing section; G – gas bottle; S – separator; T – thermostat; CV – control valve; LP – liquid pump; C - plate heat exchanger.](image-url)
A channel of rectangular section 30x0.8 mm$^2$ is realized in the working section. The channel is oriented horizontally. At the inlet, the temperature of the liquid and gas does not exceed 25 °C. This surface area of the local heater is 10x10 mm. The heater mounted in a stainless plate consists of three parts. The heating element was made using a 3D printer for metal EOS M 290. An aluminum powder composite was used as the material from which the heating element with micro-fins was made. The thermal conductivity of the material is about 170-180 W/m°K. The surface roughness of the heating element is about 40 microns. The first surface of the heating element has microfins in the form of cylindrical protrusions with a diameter and height of 300 μm, and the distance between the centers of the cylinders is 1 mm. The second surface of the heating element has a smooth surface. The copper frame connects the heating element and ceramic heaters into one functional part - the heater. Two ceramic heaters, built into the frame using highly heat-conducting thermal paste, allow you to create a total heat flux of up to 500 watts, but with restrictions on the operating temperature inside the heaters to 550 °C.

Visualization of the two-phase flow was carried out using a Nikon digital camera. Using the image obtained from the camera, the flow regime was determined, as well as the critical heat flux, when the heater was dried. In addition, a Titanium infrared camera was used to determine the temperature field. For this purpose, sapphire glass was used as the upper channel wall.

3. Experimental results

The surface roughness of the additive elements is about 40 μm. Studying the surface wettability of the heating element was carried out using a KRUSS DSA 100 device. The measurement of contact angle is shown in Fig 2. The hysteresis of the angle is 80°. Advancing contact angle is 100±5°, receding contact angle is 20±5°.

![Figure 2](image)

**Figure 2.** The photos of measurement of contact angle: advancing contact angle (left image) and receding contact angle (right image).

Experiments on heat and mass transfer in a two-phase system with two types of heating element surface were conducted. The dependence of the critical heat power ($Q_{cr}$) on the superficial gas velocity ($U_{SG}$) excluding heat losses is shown in Fig. 3. The range of superficial liquid velocity ($U_{SL}$) is from 0.013 to 0.026 m/s. The range of superficial gas velocity ($U_{SG}$) is from 3.5 to 17.4 m/s. In fig. 2, points «1», «2», «3» are obtained for a smooth surface of heater. Points «4», «5», «6» are obtained for surfaces of heater with micro cylinders. The flow regime in the experiments maintained the stratified regime. The critical heat power was defined as:

$$Q_{cr} = UI$$  \hspace{1cm} (1)

Where $U$ is the voltage value on the ceramic heater, $I$ is a amperage on the ceramic heater, $S$ is the surface area of the additive heater. It is seen that for a smooth heater, the dependence of the critical heat power on the superficial gas velocity has a classical character. With an increase in the superficial gas velocity, the critical heat flux in a two-phase system increases.

Dependence for a surface with micro cylinders is more complex. For $U_{SL} = 0.013$ m/s, the dependence of the critical heat power on the superficial gas velocity has a classical character as with a smooth heater.
For $U_{SL} = 0.018$ m/s and $U_{SL} = 0.026$ m/s, the dependence of the critical heat power on the superficial gas velocity has reverse character. With an increase in the superficial gas velocity, the critical heat power in a two-phase system decreases. This phenomenon may be due to the thickness of the liquid film. As the superficial liquid velocity increases, the film thickness decreases. This leads to the fact that at a critical thickness less than the height of the micro-cylinder, the liquid film begins to collapse. The destroyed film breaks up into large liquid drops and liquid slugs, some of which do not fall on the surface of the heater. This was observed visually. Destruction of an effective evaporative liquid film leads to a decrease in heat transfer.

**Figure 3.** The dependence of the critical heat power on the superficial gas velocity.

For smooth surface: 1 – $U_{SL} = 0.0145$ m/s, 2 – $U_{SL} = 0.0175$ m/s, 3 – $U_{SL} = 0.02$ m/s.

For surfaces with micro cylinders: 4 – $U_{SL} = 0.013$ m/s, 5 – $U_{SL} = 0.018$ m/s, 6 – $U_{SL} = 0.026$ m/s.

The liquid inlet temperature is 25°C.

When comparing the critical heat power values for a smooth heater and a heater with cylindrical protrusions, it is seen that, with comparable values of the fluid velocity $U_{SL} = 0.0175$ m/s and $U_{SL} = 0.018$ m/s, the critical power is higher in the case of a heater with cylindrical protrusions. This phenomenon is observed for the superficial gas velocity from 7 to 10 m/s. This phenomenon can also be due to the fact that on the heater, due to the cylinders, many sections are formed with a thin liquid film, which, with an increase in the superficial gas velocity, are more strongly destroyed and scattered outside the heater zone.

A detailed study of this phenomenon can lead to the creation of a new energy-efficient minichannel configuration for a two-phase system that can increase the critical heat flux without significantly increasing the superficial gas velocity.

**Conclusions**

In this study, the dependence of the critical heat power on the superficial gas velocity for two type of heater surface was studied. It is shown that for smooth heater dependence has classical character. It is shown that for heater with micro cylinders is different which depends on the thickness of the film and the height of the cylindrical protrusions. Comparison of critical heat powers for a smooth heater and a heater with microcylinders showed that for a superficial liquid velocity of 0.0175 and 0.018 m/s, the value of the critical heat flux for a heater with micro-fins can be higher for a superficial gas velocity $U_{SL} = 7.5$ m/s (70% higher), $U_{SL} = 8.7$ m/s (18% higher), $U_{SL} = 9.3$ m/s (10% higher). Further study of the mechanisms of this phenomenon will allow us to create an effective cooling system with a minimum flow rate of gas in comparison with a two-phase system with a smooth channel.
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