Thin film evaporative cooling system for high heat flux applications

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Abstract. One of the promising ways of removing large heat fluxes from the surface of heat-stressed elements of electronic devices is the use of evaporating thin layer of liquid film, moving under the action of the gas flow in a flat channel. In this work, a prototype of evaporative cooling system for high heat flux removal with forced circulation of liquid and gas coolants, capable to remove heat flux of up to 1 kW/cm² and higher is presented. The peculiarity of the test section used in the present work is that the width of the channel is equal to the width of the heating element (1 cm). It was found that the configuration of the test section allows to get higher values of the heat flux compared with the case when the channel width is higher than the width of the heater, since in the latter case some portion of liquid is deviating from the heater due to the thermocapillary forces.

1. Introduction
One of the major problems in the field of applied thermal physics is creation of an effective cooling system for microelectronics, power chips, «green» IT. Modern cooling systems for processors are able to remove up to 150-200 W/cm². Development of more effective and compact cooling system for electronics will lead to rapid development of powerful microelectronics. Today, in DATA centers, about 30-40% of all energy is used by cooling system. Currently, the global industry is ready to produce high-performance electronic components where the heat flux density at individual sites can reach 1000 W/cm² and higher [1]. However, the introduction and use of these devices faces challenges of removing such high specific heat fluxes into the ambient medium.

One of the promising ways of removing large heat fluxes from the surface of heat-stressed elements of electronic devices is the use of two-phase flows in microchannels [2, 3]. The most efficient flow regime in the channel (in terms of heat removal) is annular or stratified flow [1]. Authors of [4-6] suggested to use artificially formed stratified flow in the channel, namely a thin liquid film, moving under the action of the gas flow in the channel. Recent experimental investigations conducted in works [7-9] proved possible removal of heat fluxes with density of up to 1200 W/cm² from the heating area of 1x1 cm² using this method. The works [10, 11] showed that such a system can operate stably in a wide range of the channel heights (0.17-2.00 mm) and angles of the channel inclination to the horizon (0-360°). In [12] heat transfer in a liquid film shear-driven in a channel with an extended heater has been studied (under comparatively low heat fluxes). In [13, 14] a 3D non-stationary mathematical model of joint motion of evaporating liquid film and co-current gas/vapor flow in a microchannel with local heating has been developed, taking into account a deformable gas-
liquid interface, convective heat transfer in the liquid and gas phases as well as temperature dependence of surface tension and liquid viscosity. The performed experimental and theoretical investigations have resulted in the development of a prototype of evaporative cooling system for electronic devices with high heat flux removal. The prototype has closed loops of liquid and gas circuits. In the current paper we present the results of first experiments conducted using this prototype.

2. Experimental setup
A schematic diagram of the experimental prototype of evaporative cooling system is shown in figure 1. The system has two closed working circuits: a liquid circuit and a gas circuit. The liquid circuit, as seen from figure 1, contains pump Grundfos DDE 15-4 for pumping working liquid. The gas circuit contains a membrane vacuum pump-compressor MVNK 3x4, which produces an output of up to 400 l/min of working gas. To control gas consumption, the Bronkhorst F-111AC-70K flow regulator is used, which has an operating gas flow range from 0 to 100 l/min. At the exit from the test section, the vapor-gas mixture condenses in the plate heat exchanger ACH16-14H-F. After condensation, the gas and liquid enter the separator, from which they again begin to circulate in the prototype of the cooling system.

Scheme of the test section is shown in figure 2. The test section consists of a thin and flat stainless steel plate with a flush-mounted cooper rod with a 1x1 cm square head, serving as a heater. The temperature of the copper rod surface (substrate temperature) and the local heat flux were determined using 2 thermocouples embedded along the copper rod (at the distance of 1 and 2.5 mm from the copper surface, figure 2). The liquid film supplied from the liquid nozzle is driven by the shear stress of gas in the channel. Water and air with initial temperature of about 25°C are used as the working liquid and gas, respectively. The channel is oriented horizontally. The channel height is 1.0 mm. The peculiarity of the test section used in the present work is that the width of the channel is equal to the width of the heating element (1 cm).

Figure 1. Schematic diagram (left) and photograph (right) of the experimental prototype of evaporative cooling system: TS – testing section; C – condenser; S – separator; R – receiver; CV – control valve; LP – liquid pump; CG – gas vacuum pump-compressor; BWS – building water supply.
The lower part of the copper rod is wound with an isolated nichrome tape with a known resistance (not shown in figure 2). In the process of passing an electric current through the nichrome tape, the generated Joule heat creates a heat flux inside the copper rod. The power supply AC-DC 3300W SM 100-AR-75 DLT LPF is used. The heated copper rod is covered with thermal insulation material 5 mm thick (not shown in figure 2).

3. Experimental results
Experiments to determine the critical heat flux were carried out. Using the built-in thermocouples, the local heat flux was determined. The determination of the heat transfer crisis was detected as sharp uncontrolled rise in the surface temperature of the heater (see figure 3), accompanied by dryout of the heater and the area downstream.

![Figure 2. Scheme of the test section. 1 - liquid nozzle, 2 - stainless steel substrate, 3 - 10x10 mm² heater, 4 – outlet, 5 - copper rod, 6 - gas inlet, 7 - liquid inlet, 8 - textolite base, 9 - thermocouples «4» and «5»]

The temperature of the liquid at the inlet is 20°C.

![Figure 3. Time dependence of temperatures measured with thermocouples, showing the moment of the crisis. The local heat flux changes from 0 to about 400 W/cm². Re_{liquid} = 249 (liquid flow rate is 150 ml/min), U_{eg} = 22 m/s (gas flow rate is 13 l/min). The temperature of the liquid at the inlet is 20°C.](image-url)
Figure 4. The time dependence of the heat flux. $Re_{\text{liquid}} = 249$ (flow rate of liquid 150 ml/min), $U_{sg} = 22$ m/s (flow rate of gas 13 l/min). The temperature of the liquid at the inlet is 20°C. $Q_1 = 201$ W/cm$^2$, $Q_2 = 298$ W/cm$^2$, $Q_3 = 400$ W/cm$^2$, $Q_4 = 503$ W/cm$^2$.

Figure 4 shows the time dependence of the local heat flux and heat flux determined by the electrical power dissipated on the heating spiral, $Q$. It is seen that with the increase in the heat flux the relative difference between the total and local heat flux decreases from about 25 to 15 percent.

Data on the critical heat flux, for Reynolds number of liquid 249 and 426 and different superficial gas velocities, is shown in figure 5. It can be seen from figure 5 that the value of the critical heat flux obtained in our work is higher for the same liquid flow rate with respect to the results from the work [9], where the width of the flow (3 cm) is three times the width of the heater (1 cm). We use a test section with the flow width equal to the width of the heater (1 cm). Such a comparison proves the effectiveness of using such a configuration of the test section. However, the wall temperature is higher than 100°C, which cannot be used for practical applications for microelectronics, but when the pressure is lowered or another fluid with a lower boiling point is used, it can be reduced to the operating temperature of microelectronics. The most important technical problem in the experiment is the creation of high heat fluxes, since the nichrome spiral burns out with time and does not withstand long thermal overloads.

Figure 5. Critical heat flux vs. superficial gas velocity.
1 - Liquid flow rate = 150 ml/min, 2 - Liquid flow rate = 250 ml/min; 3 - data from [9], liquid flow rate = 150 ml/min, 4 - data from [9], liquid flow rate = 350 ml/min.
4. Conclusions
A prototype of evaporative cooling system for high heat flux removal with forced circulation of liquid and gas coolants, capable to remove heat flux of up to 1 kW/cm² and higher was elaborated. The width of the test section channel is equal to the size of the heater (1 cm). It is proved that such configuration of the test section will allow to get higher values of the heat flux compared with the case when the channel width is higher than the width of the heater (at the same liquid flow rate), since in the latter case some portion of liquid is deviating from the heater due to the thermocapillary forces. It is also shown that the heat loses decreases with increasing value of the heat flux.

Acknowledgements
The work was supported by Russian Science Foundation, Project No. 14-19-01755. The test section was built under the support of FASO Russia.

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