Prospects for using two-phase micro-size systems for high heat flux removal

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Abstract. Heat transfer in active systems for high heat removal based on the micro-channels and hybrid micro-channel/micro-jet is considered. The application of these systems allows significantly increasing the critical heat flux for a dense arrangement of the heat stressed equipment. The characteristics of heat transfer and critical heat flux during subcooled flow boiling of water in the micro-channel heat sink and during micro-jet impingement in narrow channel are obtained. The experiments are performed for the horizontal segmented microchannels with a cross section of 340×2000 μm² made on the top of copper target and for impingement micro-jet cooling of the copper target in the gap of 1000 μm. It has been found that, compared with impingement micro-jet cooling in similar condition, the micro-channel cooling is more effective for high heat flux removal although it creates the considerably high wall temperature.

1. Introduction

Achievements in the field of miniaturization and increasing performance of the computer microprocessors necessitate the search for the effective methods for removing high heat fluxes from small-sized heat-stressed equipment. Heat fluxes for the computer microprocessors already exceed 100 W/cm² [1], while for the lasers, microwave devices and radars they can considerably exceed this value. Therefore, traditional methods using air cooling become ineffective. As applied to small-sized heat-generating devices, two-phase microchannel cooling systems are capable of removing high heat fluxes at low mass flux and pressure drop, especially during subcooled liquid boiling [1].

There is serious limitation for the use of micro-channel cooling systems due to the appearance of the premature boiling crisis [2]. Therefore, recently much attention is given to the search for methods critical heat flux increase. Among the processes leading to a premature boiling crisis, there is a steam release from the microchannels at the onset of nucleate boiling [1, 2]. The use of hybrid cooling systems that combine the advantages of the micro-channels and impingement micro-jets can avoid this phenomenon and remove higher heat fluxes [3]. The aim of this work is to study the effect of the mass flux and heat flux on heat transfer and critical heat flux during subcooled flow boiling of distilled water in segmented narrow micro-channels and in impingement micro-jets to compare their efficiency.
2. Experimental equipment and methods

The schematic of the experimental equipment is shown in figure 1. The experiments were performed at constant liquid flow rate, which was set by a Seko Spring PS1 pump through pulsation damper and measured by a LIQUI-FLOW L30 flow controller. At the exit of the heat exchanger, atmospheric pressure was maintained. The test section for studying the flow boiling heat transfer in a micro-channel heat sink is shown in figure 1 (a). The copper block with two micro-channels with the length of 16 mm, width of 2000 μm and depth of 340 μm, separated by a 2000 μm thick baffle was closed by polished stainless-steel top cover. Micro-channels were made by milling the top surface of copper block (target) which was covered with a protective 2 μm thick nickel layer. On the inner surface of micro-channels, the microstructured coating with a thickness of 20 μm was applied using electrochemical treatment with SiO$_2$ nanoparticles. The RMS surface roughness, determined from the measurements at an interference profilometer, was 2.2 microns. The inlet and outlet distribution chambers with a diameter of 8 mm and length of 6 mm were thermally insulated from the copper block using paronite gaskets. The large ratio of the cross-section of the distribution chamber to the flow area serves to create conditions for the complete condensation of steam ejected from micro-channels into the chamber when nucleate boiling occurs.

![Figure 1](image)

**Figure 1.** Scheme of experimental section with segmented micro-channels (a) and impingement micro-jets (b).

The heat flux to the base of the micro-channels is supplied from heating elements shown in figure 1 (a). In the copper block, at distances of 3 mm and 13 mm from the inlet, there are four thermocouples with a diameter of 0.5 mm, which measure the temperature at a depth of 1.2 mm and 5 mm from the inner surface of the channels. The thermocouples were calibrated using platinum resistance thermometer in the temperature range from 16 to 340°C, the temperature measurement error being 0.2°C. The measurements of flow temperature and pressure were performed in the inlet and outlet chambers. The mean heat flux density at the base of the micro-channels and the mean temperature of the micro-channels wall were determined from the measured temperature gradients in the copper block, taking into account the dependence of the thermal conductivity of copper on temperature. The mean heat flux on the microchannel wall was determined taking into account the ratio of the area of the base of the copper block to the inner area of the micro-channels. The imbalance of the amount of heat released by the elements, taking into account heat loss, and the heat transferred to the flow, do not exceed 4%.

The experimental section for studying heat transfer during impingement micro-jet cooling in the narrow channel is shown in figure 1 (b). In the course of the experiments, the axisymmetric cooling of a heat-loaded round target with the diameter of 1 cm is carried out by three micro-jets with diameter of 450 μm. The size of the narrow gap between the nozzles and the cooled surface is adjustable, and in the performed series of the experiments varies from 600 to 1000 μm. The top surface of the copper
block, polished to a mirror finish, was used as a heat-loaded target. Along the length of the copper block, four K-type thermocouples with a diameter of 0.5 mm are mounted along its axis at the distance of 1; 3; 5.3; 7.2 mm from the top surface. The extended base of the copper cylinder is housed by the heating elements and insulated thermocouple.

3. Experimental results
Figure 2 shows the experimental data of the heat flux dependence taken from surface of the segmented micro-channels on inner wall temperature (boiling curve). The experiments were performed at inlet water temperature equal to 25 °C for two mass fluxes of 330 and 500 kg/m²s. The arrows in the figure show the critical heat fluxes for this case. The solid line in the figure shows the prediction of the boiling curve for pool boiling of water according to [4]. The dashed line shows the prediction of single-phase convection in developing laminar flow during three-sided heating [5] at mass flux of 326 kg/m²s. Accounting that the aspect ratio of used microchannel equals to 5.88, the prediction is obtained using the correlations for the mean Nusselt number for thermally developing flow between parallel plates as follows

\[
Nu_m = \begin{cases} 
  2.236 \cdot x^*^{-3/3} + 0.9 & 0.001 < x^* \leq 0.01 \\
  8.235 + 0.0364/x^* & x^* > 0.01 
\end{cases}
\]

Figure 2. Dependence of heat flux on wall temperature during the flow in a segmented slot micro-channel heat sink.

As is seen, if the wall temperature is less than the nucleation temperature, the heat transfer coefficients correspond well to the experimental data. During subcooled nucleate boiling, when the wall temperature rises above the saturation temperature, an increase in the mass flux leads to the enhancement of heat transfer. The nucleate boiling arises before prediction [4] because the inner surface of microchannels is covered by nickel layer with SiO₂ nanoparticles. With an increase in the heat flux, the deterioration in heat transfer is observed in comparison with the pool boiling, which indicates the suppression of the nucleate boiling when large vapor bubbles in micro-channel arise.

When surface is cooled by impingement micro-jets of subcooled water, an increase in the heat transfer and critical heat flux can be expected due to decrease of the vapor volume fraction near the wall. In figure 3 the dependence of the heat flux taken from target surface by micro-jets on the wall temperature is shown at inlet water temperature of 22 °C and jet velocity of 3.2 and 7.5 m/s. As is seen, increasing superficial velocity of the coolant in micro-jets, significantly increases the critical heat flux and decreases the wall temperature.
Figure 3. Dependence of heat flux on wall temperature during impingement micro-jet cooling in narrow gap.

The experimental data on the dependences of heat flux on the wall temperature during flow boiling of water shows that micro-channel heat sink with extended inlet chamber and high aspect ratio of the channels has high efficiency for heat flux removal from the local heat sources due to suppression of the premature boiling crises. The targets used in the tests with micro-channel cooling and impingement jet cooling have approximately the same heated surface area, about 80 mm$^2$. Comparing the data presented in figures 2 and 3 one can see that micro-channel cooling by water allows removing 479.3 J/g heat from the target at mass flux of 500 kg/m$^2$s compared with 338.8 J/g for impingement micro-jet cooling at superficial velocity of 3.2 m/s. It shows more efficient cooling in case of microchannels but for considerably high wall temperature, see figures 2 and 3.

Conclusions
The presented results show high efficiency of slotted micro-channels for high heat flux removal. An increase in the size of the inlet chamber and target surface treatment using SiO$_2$ nanoparticles is found to prevent the development of dry areas and suppresses the premature boiling crises which increases the critical heat flux. It has been shown that using hybrid cooling systems combining the advantages of micro-channel and impingement micro-jets allows removing heat fluxes of up to 900 W/cm$^2$ at smaller wall temperature that in case of micro-channel cooling.

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