Influence of heater size on critical heat flux in flat microchannels with intense localized heating

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Abstract. Experiments were carried out on flow boiling in mini- and micro- channels under local heating for different heater size. It was found that with an increase in the channel height in the range of 0.2–3.7 mm, the intensity of heat transfer and the critical heat flux increase significantly. For a given flow rate and channel height, the critical heat flux on the 3x3 mm^2 heater exceeds the heat flux on the 10x10 mm^2 heater, and the difference increases with increasing channel height. Boiling curves were also obtained.

1 Introduction

Forced convection boiling is an effective cooling technique for temperature management in heat loaded applications. The rapid development of microelectronics, due to the ever-increasing needs for computing power, sets before scientists and engineers the task of effective temperature control at the microlevel for promising microprocessors [1, 2]. The volumetric heat flux in three-dimensionally integrated microprocessors of such applications already reaches 10 kW/m^3 [2], and the heat flux distribution in such processors can be very uneven. In addition to this, a new generation of power electronics based on GaN transistors has already been developed, which has the characteristics required for high density energy conversion, which will require intensive cooling, [3].

Flow boiling in channels and minichannels has being actively studied [4–5]. For example, in [6], the influence of the aspect ratio in the flow boiling in a microchannel with uniformly heated wall was studied, and the authors found that this ratio has a great influence on the heat transfer coefficient. In [7], the saturated boiling of water in silicon microchannel sink with a constant hydraulic diameter and different aspect ratios of the microchannels was studied. The aspect ratio has been found to have a great influence on the heat transfer characteristics. However, the key problems of wall overheating, the inherent instability of the flow, and low values of the critical heat flux in conventional continuous parallel microchannels create serious problems for the practical application of microchannel heat sinks in devices with a high heat flux, [8]. In [9], the influence of the channel height on heat transfer and the critical heat flux in flat minichannels with inhomogeneous heating (the flow width is greater than the heater width) was studied. However, the influence of the ratio of the heater to the channel width is not well understood, although it can have a significant effect on the boiling heat transfer efficiency in mini- and microchannels.

The aim of the current work is to study the effect of channel to heater width ratio on critical heat flux during flow boiling in mini- and microchannels. In this work, systematic studies of boiling heat transfer with non-uniform heating in mini- and microchannels of height from 0.2 to 3.7 mm were carried out with sizes of the heater 3*3 and 10*10 mm^2, while the channel width was the same (30 mm). The experiments were carried out with intense heating from the side of the wall (up to 1 kW/cm^2 from the 10x10 mm^2 heater and up to 1.6 kW/cm^2 from the 3x3 mm^2 heater).

2 Experimental setup

Two test sections were used. The first one has a 3x3 mm^2 heater and is shown in Fig. 1 and Fig. 2. The upper wall of the channel consists of 20 mm thick anti-reflective glass, which makes it possible to visualize the hydrodynamics of the boiling process. The lower part of the channel is a stainless steel plate into which a copper rod with a 3x3 mm^2 head is pressed, which acts as a heater. Using 2 thermocouples, 0.25 mm in diameter, embedded in the heater, and 6 thermocouples, 0.5 mm in diameter, embedded in the steel plate, the heat flux in the copper rod is determined, as well as heat losses into the stainless-steel plate. To minimize radiative heat losses, the outside of the copper heater has been nickel-plated. As a heat source, 4 cartridge heaters with heating power of 160 W each are used. Thermal contact between cartridge heaters and copper is provided by a thin layer of liquid metal thermal interface based on gallium alloy. The copper heater block is wrapped in airgel sheets with thermal conductivity of 0.019 W/(m·K) at room temperature, which greatly reduces heat losses to the atmosphere. The heat flux from the heaters is defined as the heat flux along the copper rod, measured with thermocouples, minus the heat loss into the plate. Fluid was supplied to the working area by means of a flow pump and additionally the flow was measured by means of an ultrasonic flow meter. Milli-Q ultrapure distilled water was used as the working fluid. Channel height is measured at 6 points using a Micro-Epsilon IFC2451 confocal probe. Visualization was performed using a FASTCAM SA 1.1 high-speed camera. The shooting speed in the experiments reached 100,000 frames per second. The camera is equipped with a high spatial resolution optical system, in particular the Mitutoyo M PLAN APO x5 lens, which allows achieving a spatial resolution of 2 microns per camera pixel.

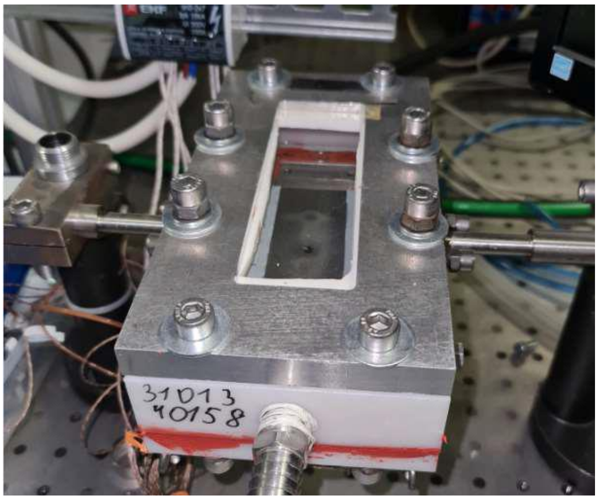

Fig. 1. Photo of the test section with heater sized 3x3 mm^2.

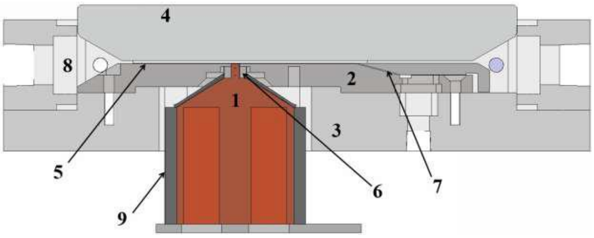

Fig. 2. Schematic of the test section with heater of 3x3 mm^2. 1 - Copper heater, 2 - stainless steel plate, 3 - caprolon base, 4 - glass top cover, 5 - fluoroplastic insert, 6 - fluoroflagopite gasket, 7 - liquid inlet nozzle, 8 - outlet nozzle, 9 - airgel thermal insulation.

The second test section has a heater of size 10x10 mm^2 and is shown in Figs. 3 and 4. The upper wall of the channel consists of 15 mm thick anti-reflective glass. The lower part of the channel is a stainless steel plate into which a copper rod with a head 1x1 cm^2 is pressed, which acts as a heater. With the help of 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 flux in the copper rod, as well as heat losses into the stainless-steel plate, is determined. To minimize radiative heat loss, the outside of the copper heater was nickel-plated. As a heat source, 7 cartridge heaters with heating power of 500 W each are used. Thermal contact between cartridge heaters and copper is provided by a thin layer of liquid metal thermal interface based on gallium alloy. The copper heater block is wrapped in airgel sheets with a thermal conductivity of 0.019 W/(m·K). The heat flux from the heater is defined as the heat flux along the copper rod, measured with thermocouples, minus the heat leakage into the plate. Methodology of calculation of the local heat flux in these experimental setups is described in [10].

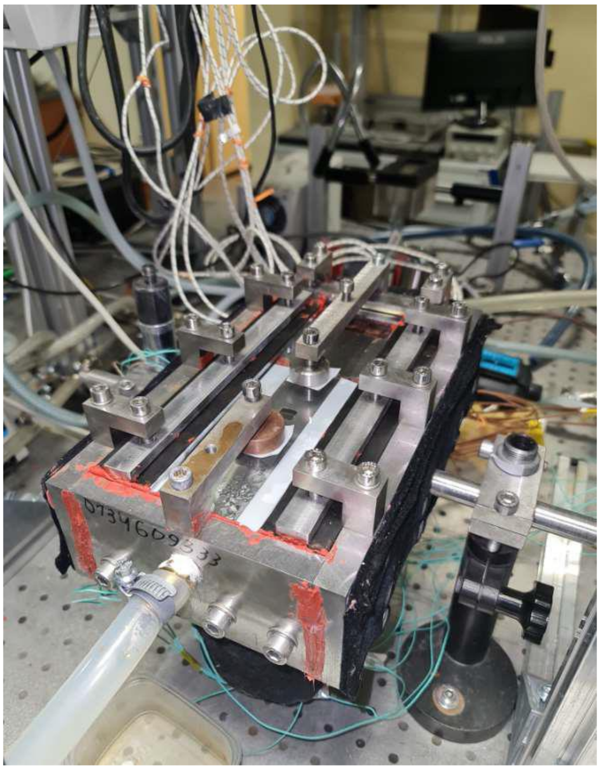

Fig. 3. Photograph of the test section with heater of 10x10 mm^2 and heating power of up to 3.5 kW.

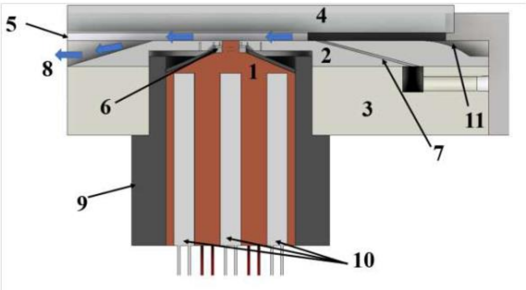

Fig. 4. Schematic of the test section with heater of 10x10 mm^2. 1 - Copper heater, 2 - stainless steel plate, 3 - TECAPEEK base, 4 - glass top cover, 5 - PTFE insert, 6 - paronite gasket, 7 - liquid inlet nozzle, 8 - outlet nozzle, 9 - airgel thermal insulation, 10 - cartridge heaters, 11 - gas inlet.

3 Results and discussion

It was found that with an increase in the channel height, the intensity of heat transfer and the critical heat flux increase significantly (Fig. 5). Qualitatively, the results obtained for heaters 3x3 and 10x10 mm^2 are identical. However, for a given flow rate and channel height, the critical heat flux on the 3x3 mm^2 heater exceeds the heat flux on the 10x10 mm^2 heater, and the difference increases with increasing channel height (see Fig. 6). Since we have a proven method for calculating heat losses and heat fluxes in such a channel [10], it is unlikely that the observed phenomena are the result of an error in processing experimental data.

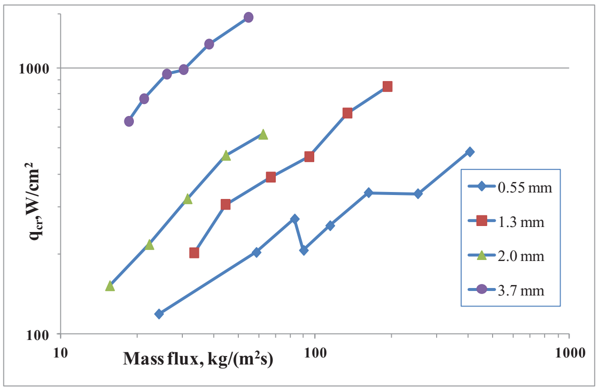

Fig. 5. Effect of specific mass flow rate (mass flux) and channel height (indicated in the legend) on the critical heat flux. $\mathbf{q_{cr}}$ is the critical heat flux (W/cm^2). Water, heater 3x3 mm^2, channel width 30 mm.

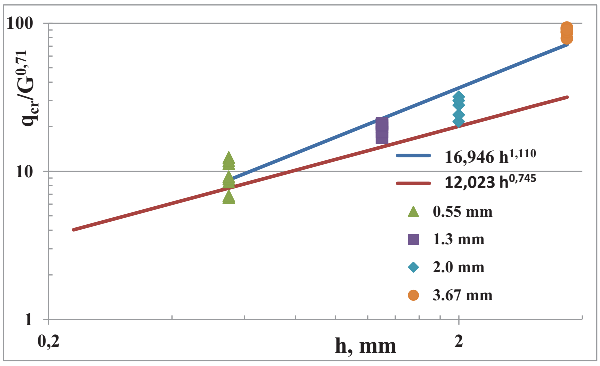

Fig. 6. Influence of the channel height on the reduced critical heat flux for 3x3 mm^2 heater (points, blue generalizing line) and 10x10 mm^2 heater (red generalizing line). Water, channel width 30 mm. $\mathbf{q_{cr}}$ is the critical heat flux (W/cm^2), **G** is the mass flux (kg/m^{2}s), **h** is the channel height (mm).

Boiling curves are obtained for various water flow rates at various channel heights for both heater sizes. An example of boiling curves for a 2.0 mm height channel for two heater sizes is shown in Fig. 7.

The behaviour of the boiling curves is generally similar for both sizes of the heater in the entire range of water flow rates and channel heights. It is described in detail for the heater with the size of 10x10 mm^2 in [9] and compared with the case of uniform heating in [11].

Conclusions

Flow boiling experiments were carried out in mini- and microchannels with different heater sizes. It was found that with an increase in the channel height in the range of 0.2–3.7 mm, the intensity of heat transfer and the critical heat flux increase significantly. For a given flow rate and channel height, the critical heat flux on the 3x3 mm^2 heater exceeds the heat flux on the 10x10 mm^2 heater, and the difference increases with increasing channel height. The behaviour of the boiling curves is generally similar for both heaters.

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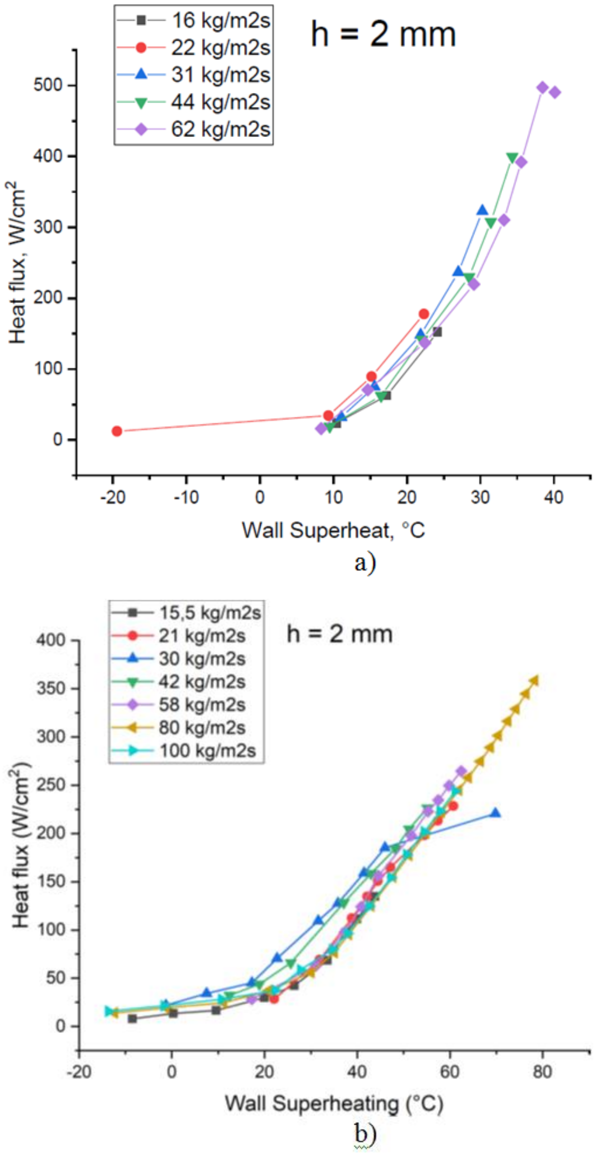

Fig. 7. Flow boiling heat flux under local heating vs. wall superheating temperature. Channel height **h** is 2 mm. The heater size: a) 3x3 mm^2, b) 10x10 mm^2.

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