Influence of channel to heater width ratio on flow boiling critical heat flux in mini- and microchannels

D V Zaitsev1,2 and V V Belosludtsev1,2

1 Kutateladze Institute of Thermophysics SB RAS, 630090, Novosibirsk, Russia
2 Novosibirsk State University, 630090, Novosibirsk, Russia

E-mail: v.belosludtsev@nsu.ru

Abstract. Flow boiling experiments were conducted in mini- and microchannel with different ratio of heater width to a channel width. Decrease in critical heat flux is observed in transition from wide channel to channel with width equal to a heater width. Particularities of boiling phenomena in these conditions were observed by means of high-speed visualization, which provided an explanation to heat flux reduction.

1. Introduction

Forced convection boiling is an efficient cooling method of thermal management in high power applications. The rapid development of microelectronics driven by ever increasing needs in computing power sets a goal for scientists and engineers of efficient thermal management on a microscale for future-proof microprocessors [1, 2]. Projected volumetric heat flux in such applications is expected to reach 10 kW/m³ [2] in three-dimensionally integrated microprocessors and distribution of heat flux can be highly uneven in such processors. In addition to cooling of future microprocessors there is a next generation of power electronics which is based on GaN transistors and it has exceptional characteristics for high density power conversion applications and, therefore, it will require intensive cooling.

Particularities of flow boiling is being widely studied. For example, the effect of aspect ratio in microchannel flow boiling was studied in [3] and authors found that aspect ratio has great impact on heat transfer coefficient during flow boiling in microchannel heat sink with uniformly heated wall. In [4] authors examined saturated flow boiling of water in silicon microchannel heatsinks with constant hydraulic diameter and different aspect ratios of microchannels. It was found that aspect ratio has great impact on heat transfer characteristics. But the effect of heater to channel width ratio is not widely studied while it may have a significant impact on flow boiling performance in mini- and microchannels.

As shown in [5], in the case of uneven heating in the mini- and microchannel, vapor bubbles can get clung in the heating area, which leads to the formation of a dry spot covering the heater, which significantly affects heat transfer and usually leads to a heat transfer crisis. To study the dynamics of bubbles at the microlevel, an ultrahigh spatial and temporal resolution is required (a typical vapor bubble reaches a size of ~30 μm during the first microsecond of its life). A technique for studying the dynamics of vapor microbubbles in microchannels with a shooting frequency of up to 775,000 frames per second was developed by the authors in [6].

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.
2. Experimental setup

Flow boiling experiments were conducted in the experimental setup which is consisted of visualization system, test channel, liquid supply circuit and measurement system.

As the working fluid deionized water obtained from Milli-Q Direct 3 UV was used in experiments. Working fluid was pumped by Cole-Parmer EW-75211-35 pump through circuit consisted of plate heat exchanger, ultrasonic flowmeter and test channel. In the plate heat exchanger liquid was cooled to required temperature of 25±0.4°C by means of Huber MPC-K6 thermostat and it was additionally controlled by thermocouple at the inlet of test channel. Flow rate of working fluid was set by means of Cole-Parmer pump and controlled by ultrasonic flowmeter. Since the liquid tank is open to the atmosphere, the experiments are done under normal pressure, with the pressure drop along the test channel does not exceed 4000 Pa, as measured by WIKA-P30 pressure transducers.

![Figure 1. Scheme of the experimental setup.](image)

The test channel consists of textolite frame with the stainless-steel working plate and embedded copper heater. The working surface of copper heater is a square with dimensions of 1x1 cm and it is connected together with stainless-steel plate to form a flat surface with RMS roughness 0.79 µm measured by atomic force microscope. Around the copper heater rod a nichrome wire wound and it is connected to a direct current power source. Thermal insulation is provided by mineral wool wounded around the rod with nichrome wire. To form a channel with desired height and width, changeable PTFE inserts are placed in between stainless-steel surface and top transparent flat glass window. The channel height in experiments was 0.4 and 1 mm and it was verified by Micro-Epsilon confocal sensor, with the unflattens of the channel not exceeding 10% for all channels. The width was either 10 or 32 mm for both cases of the channel heights. This provided a uniform heating condition when channel width was equal to heater width, i.e. 10 mm, or non-uniform heating condition (localized heat source) in the wide channel with width of 32 mm. Visualization setup consisted of Photron FASTCAM SA 1.1 equipped with Nikkor 105 mm AF-S Micro lens providing possibility to observe whole working area of the copper heater in details. The speed of recording was from 5400 frames per second (fps) at the resolution of 1024x1024 pix and up to 15 000 fps at resolution reduced to 768x512 pix.

Methodology of calculating heat losses and heat fluxes in this test channel is described in [7, 8]. Verification of this methodology is done in [9].
3. Results and discussion

Two main boiling regimes were observed during experiments. Nucleate boiling regime was observed at relatively low wall superheat temperature up to 40°C and with increase of wall superheat temperature a transition to unstable boiling regime was observed. The unstable boiling regime could be described as oscillation of a single large vapor bubble on a heater surface (Fig. 2 and 3). In a wide channel bubble expands and shrinks almost without any noticeable highlighted direction in the channel with height of 0.4 mm, since speed of those oscillations is higher than liquid flow speed along channel (Fig. 2). In a wide channel with height of 1 mm bubble tends to stretch along flow direction (Fig. 3) but with approach to critical heat flux there is again no highlighted direction for bubble oscillations. The opposite is observed in narrow channel (Fig. 4): large bubble elongates along the direction of liquid flow as expected, similar was observed in [10]. As hydrodynamics of boiling in wide and narrow channel differs and so hydrodynamics of boiling heat transfer crisis is also different. In wide channel bubble cling at top wall and covers entire area of heater which leads to rather rapid and uncontrollable rise of the heater wall temperature, as liquid flows around clung bubble and cannot flush the heater surface. In a narrow channel bubble cannot clung for a long time since liquid flow rate is maintained constant and, therefore, bubble is periodically pushed from the heater surface. This mechanism also leads to relatively slow but periodic rise of the heater wall temperature.

![Figure 2. Oscillations of a large vapor bubble during flow boiling in wide channel, channel height is 0.4 mm. q = 216 W/cm², G = 150 kg/m²s. Recording speed is 7 500 frames per second (time in between first and last frame is 14.5 ms).](image)

![Figure 3. Oscillations of a large vapor bubble during flow boiling in wide channel, channel height is 1 mm. q = 285 W/cm², G = 100 kg/m²s. Recording speed is 5 000 frames per second (time in between first and last frame is 340 ms).](image)
Figure 4. Oscillation of large bubble during flow boiling in channel with heater width equal to channel width, channel height is 1 mm. $q = 190\ \text{W/cm}^2$, $G = 167\ \text{kg/m}^2\text{s}$.
Recording speed is 15 000 frames per second (Time in between first and last frame is 125 ms).

Figure 5. Critical heat flux for mini- and microchannel with different channel height and width (wide – 32 mm, narrow – 10 mm).

Data on critical heat flux during flow boiling on local heater in wide channel is compared to data in narrow channel (heater width equal to channel width) in Fig. 5. As can be seen from the graph, for both channel heights (0.4 and 1 mm) a decrease in critical heat flux is observed as a result of transition from wide to narrow channel. This could be explained by above-described hydrodynamics of unstable boiling regime. In a narrow channel (localized heat source) oscillating bubble is effectively being flushed by liquid from all sides resulting in higher volumetric flow rate as mass flux is constant along the width of the channel. On the contrary, in the narrow channel (heater width equal to channel width) there is no additional fluid could be sucked during unstable boiling regime from the lateral sides of a channel. Since we have a verified methodology of calculating heat losses and heat fluxes in this test channel [7-9], it is highly unlikely that observed phenomena is a result of experimental data processing error.

Conclusions
Flow boiling experiments were conducted in mini- and microchannel with different ratio of channel to heater width. With a help of high-speed visualization qualitative hydrodynamics of boiling was observed and analysed. A decrease of critical heat flux by transition from channel with higher aspect ratio to a
channel with lower aspect ratio, where heater width equal to channel width, is observed and explained by hydrodynamics of boiling. Obtained data show that bubble can reach diameter of channel height in less than 1 ms, which can lead to heat transfer crisis in channels with local heating. Observed phenomena shows the importance of study of boiling under unevenly distributed heat flux conditions.

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References
[1] Kabov O A, Zaitsev D V, Cheverda V V and Bar-Cohen A 2011 Experimental Thermal and Fluid Science 35(5)
[2] Bar-Cohen A and Wang P 2012 The Journal of Heat Transfer 134(5)
[3] Fu B R, Lee C Y and Pan C 2013 International journal of heat and mass transfer 58
[4] Markal B, Aydin O and Avci M 2016 International Journal of Heat and Mass Transfer 93
[5] Zaitsev D, Tkachenko E, Belosludtsev V, Kreta A and Kabov O 2018 Journal of Physics: Conference Series 1105(1)
[6] Belosludtsev V V and Zaitsev D V 2020 AIP Conference Proceedings 2212(020011)
[7] Zaitsev D V and Tkachenko E M 2019 Journal of Physics: Conference Series 1369(1)
[8] Tkachenko E M and Zaitsev D V 2019 AIP Conference Proceedings 2135 020057
[9] Belosludtsev V V, Tkachenko E M and Zaitsev D V 2021 AIP Conference Proceedings 2337(1)
[10] Nasr M H, Green C E, Kottke P A, Zhang X, Sarvey T E, Joshi Y K and Fedorov A G 2017 Journal of Heat and Mass Transfer 108