Subcooled flow boiling in a flat mini-channel under local heating

Dmitry Zaitsev$^{1,2}$, Egor Tkachenko$^{1,2}$, Valentin Belosludtsev$^{1,2}$, Alexey Kreta$^4$ and Oleg Kabov$^{1,2}$

$^1$Kutateladze Institute of Thermophysics SB RAS, 1, Lavrentiev Ave, Novosibirsk, 630090, Russia
$^2$Novosibirsk State University, 2, Pirogova str., Novosibirsk, 630090, Russia

E-mail: zaitsev@itp.nsc.ru

Abstract. With the help of advanced optical system having high spatial and time resolution, the dynamics of microbubbles was investigated during nucleate boiling of subcooled water flow in a mini-channel under localized heating from the wall. Substantial discrepancy in maximum bubble diameters was observed for the same experimental conditions. However, the growth rate for different bubbles within first 0.1 ms of their life time is almost the same. The data on the bubble dynamics was successfully generalized using available correlations from the literature. Data on the critical heat flux was obtained for different channel heights. A considerable effect of the channel height on CHF was found.

1. Introduction

One of the main trends in the development of modern technologies is the miniaturization of devices [1]. In many technologies, there is a transition from processes of heat and mass transfer in a large volume to processes in mini- and microsized devices. The surface and bulk density of heat fluxes increases substantially. There are four main ways to remove ultrahigh heat fluxes from localized heat sources: 1) boiling of liquid in mini and micro-channels [2], 2) spray cooling [3], 3) micro-jet cooling [4], and 4) cooling by evaporation of a thin liquid film shear-driven in a channel [5,6]. At present, the system with boiling in mini- and micro-channels is considered very promising for many applications. This system is capable of removing high heat fluxes with minimum flow rate of the working fluid and maintaining low temperature of the channel walls [7]. The use of microchannels is perhaps the only effective solution for thermal management of future microelectronics with 3D chip architecture.

In the majority of previous studies on flow boiling in mini- and microchannels an uniform heating of the channel is used (see for example [8,9]). Bar-Cohen et al. [10] described the M-shaped curve of the heat transfer coefficient vs. vapor quality for a two-phase flow in a channel in a wide range of experimental parameters. The second peak of the M-shaped curve is located in the annular flow regime and is associated with an increase in the heat transfer coefficient due to the thinning of the evaporating thin liquid film. As regards to bubbles dynamics during nucleate boiling, the majority of authors studied bubbles of millimetre size and larger (see for example [11]). Data about growth of microscale bubbles is quite limited.
The main purpose of our paper is to study the boiling of subcooled water flow in a flat mini-channel under local heating from the wall. With the help of high-speed visualization with high spatial resolution, the dynamics of microbubbles formed during nucleate boiling is investigated. The effect of the channel height on the critical heat flux is studied.

2. Experimental setup
Investigations were conducted on the experimental setup shown in Fig. 1. The setup consists of the following components: test section, liquid circuit, thermal stabilization circuit, optical system of high resolving power with high speed camera, and measurement system.

Liquid was supplied to the test section with the help of the gear pump Ismatec Reglo Z-183. Degassed ultra-pure Milli-Q water was used as the working liquid. The liquid flow rate was adjusted manually by means of the pump in the range from 4.2 to 420 ml/min. The liquid enters the circuit with a plate heat exchanger, in which, with the aid of a thermostat, the temperature of 25 °C is maintained. In this circuit, the liquid was thermally stabilized to the required temperature and after that it enters the test section. The temperature of the liquid at the inlet to the test section was controlled by means of a thermocouple integrated into the test section. The deviation of the temperature of the working liquid at the inlet to the test section from 25 °C during the experiments was no more than ± 0.4 °C. The experiments were carried out under normal pressure. Pressure at the inlet and outlet of the channel was measured by pressure sensors. The pressure drop along the channel in the experiments did not exceed 0.2 Bar.

The test section consists of a thin and flat plate of stainless steel with a flush-mounted copper rod having a square head of 1 × 1 cm serving as a heater (Fig. 1). The rod is electrically heated from below using a nichrome wire. The design of the heater provides constant temperature on the surface of the rod, \( T_w = \text{const} \) (as confirmed by thermocouple measurements). The test section is covered with a transparent glass cover. Changeable inserts are placed between the working substrate and the glass cover, so that a channel with a variable height is formed. The height of the channel \( H \) varies from 1.0 to 2.0 mm. The
width of the channel is 30 mm, i.e. 3 times the width of the heater. The working surface (stainless steel plate with copper rod) was rough polished. The morphology of the working surface was analysed using an atomic force microscope. The root mean square (RMS) surface roughness was found to be 0.79 µm.

Visualization of the process of boiling on the heater was carried out using a high-speed camera FASTCAM SA1.1. The speed of shooting was varying from 5400 frames per second at the resolution of 1024x1024 pixels to 100000 frames per second at the resolution of 300x128 pixels. The camera is equipped with an optical system of high spatial resolution (2.5 µm per 1 pixel of the camera sensor). The distance from the upper edge of the heater to the center of the field of the camera view is about 1.5 mm.

3. Results

Using high-speed visualization, a top view video of the nucleate flow boiling in the channel was recorded. Images from the video was processed using ImageJ software. In Fig. 2 the variation of diameters of six typical bubbles on the surface of the heater is presented. Due to stochastic nature of bubble formation, huge discrepancy in maximum bubble diameters is observed for the same experimental conditions. However, bubble growth rate for different bubbles within 0.1 ms of their life time is close.

![Bubble diameter vs time](image)

Figure 2. Bubble diameter vs time (channel height $H=2$ mm, heat flux $q=450$ W/cm$^2$, liquid flow rate $G_{liq}=30$ kg/m$^2$s, heater surface temperature $T_w=124$ °C, shooting rate is 40000 frames per second, distance from the upper edge of the heater to the bubbles is about 1.5 mm).

Data on bubble growth and condensation rates was normalized and fitted by the following equation:
\[
\frac{D_b}{D_{bm}} = 1 - 2^K \left[ \frac{1}{2} - \left( \frac{t}{t_b} \right)^N \right]^K
\]  

(1)

Where \( D_b \) is the bubble diameter, \( D_{bm} \) is the maximum bubble diameter, \( t \) – time, \( t_b \) - the bubble lifetime, \( N \) and \( K \) are the empirical constants (for more details see [11]). Both of the constants \( N \) and \( K \) were fitted for data in the present study and compared in Table 1 with the constants obtained in [11] where subcooled flow boiling of water was studied under pressure of 2-3 bar. Predictions obtained with Eq. (1) in [11] is compared with our data in Fig. 3. Good agreement is observed (deviation does not exceed 20 %).

Table 1. Coefficients N, K in Eq. (1) for different experiments.

| Experiment           | N   | K   |
|----------------------|-----|-----|
| Prodanovic et al. 2002 | 0.7 | 2.5 |
| Present study        | 0.75| 1.56|

Figure 3. Correlations for bubble growth and condensation rates.

Figure 4 presents the dependence of the critical heat flux on liquid mass flow rate for two different channel heights (1 and 2 mm), compared with data from the literature on flow boiling in a minichannel under uniform heating (tube with 4.8 mm diameter and 200 mm heating length, subcooling of 75 K [8]), and also in uniformly heated microchannels (heatsink with 21 channels of 231 μm width and 712 μm depth, subcooling of 70 K [9]). From Fig. 4 it is seen that with an increase of the channel height the CHF is substantially increased. We believe that this is associated with the fact that in the 1 mm channel
the bubbles (having typical maximum size of around 1 mm) can touch the glass cover and as such they can stick at the heater, leading to the occurrence of the crisis. Unlike our locally heated channel, in [8-9] uniformly heating channels were used. That is why data on CHF from [8-9] lie considerably lower than our data in Fig. 4.

![Figure 4. Comparison of the critical heat flux on the water mass flow rate for the channel height of 1 and 2 mm, compared with data on water flow boiling under uniform heating in a minichannel [8] and in microchannels [9].](image)

**4 Conclusions**

Experiments on boiling of subcooled water flow in a mini-channel under local heating, were conducted. With the help of advanced optical system having high spatial and time resolution, the dynamics of microbubbles was investigated. Substantial discrepancy in maximum bubble diameters was observed for the same experimental conditions. However, the growth rate for different bubbles within first 0.1 ms of their life time was close. The data on the bubble dynamics was successfully corelated using equations known from the literature. Data on the critical heat flux was obtained for 1 and 2 mm high channels. The channel height was found to considerably affect the CHF.

**References**

[1] D.V. Zaitsev, E.M. Tkachenko and O.A. Kabov, *EPJ Web of Conferences*, 159, 00054, 2017.
[2] J.R. Thome, *International Journal of Heat and Fluid Flow*, 25, 2004.
[3] J. Kim, *International Journal of Heat and Fluid Flow*, 28, 2007.
[4] A.J. Robinson, R. Kempers, J. Colenbrander, N. Bushnell, R. Chen, *Applied Thermal Engineering*, 136, 2018.
[5] O.A. Kabov, Yu.V. Lyulin, I.V. Marchuk, D.V. Zaitsev, *International Journal of Heat and Fluid Flow*, 28, 103-112, 2007.
[6] O.A. Kabov, D.V. Zaitsev, V.V. Cheverda, A. Bar-Cohen, *Experimental Thermal and Fluid Science*, 35, 825–831, 2011.

[7] W. Qu, I. Mudawar, *Int. Journal of Heat and Mass Transfer*, 46, 2003.

[8] W. Zhang, T. Hibiki, K. Mishima, Y. Mi, *International Journal of Heat and Mass Transfer*, 49, 1058, 2006.

[9] I. Mudawar, W. Qu, *International Journal of Heat and Mass Transfer*, 47, 2045, 2004.

[10] A. Bar-Cohen, E. Rahim, *Heat Transfer Engineering*, 30, 2009.

[11] V. Prodanovic, D. Fraser, M. Salcudean, *International Journal of Multiphase Flow*, 28, 2002.