Bubble dynamics during flow boiling in a flat 0.6 mm high channel

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Abstract. The vapour bubble dynamics during subcooled flow boiling in a flat microchannel with the height of 0.6 mm was investigated using high-speed visualization. Nucleate flow boiling was maintained by localized heat source. The data on the bubble dynamics was compared with well-known classic growth correlation formulas. The obtained data have shown that the bubble size can reach the channel height in about 0.1 ms, which can lead to heat transfer crisis in channels with local heating.

1. Introduction

Microchips and other electronics are becoming more efficient and powerful, however, the convenient methods of maintaining this trend become ever more complicated year by year. Engineers and scientist make every effort to implement new methods to increase efficiency of electronics. One of such methods is the three-dimensional integrated circuit, implemented in low energy applications such as systems on a chip in mobile devices and multilayer DRAM and NAND memory chips. Three-dimensional packaging is one of the major trends of microelectronics development, but for its successful implementation, there is a dire need of new methods of thermal control for high performance microchips [1], where local heat fluxes rise up to non-conventional values compared to modern electronics. As stated in [1] microchannel cooling is one of the most suited ways to solve thermal control problems in 3D stacked microchips. There are five known methods of removal of unevenly distributed heat flux, namely: 1) boiling of liquid in mini and micro-channels [2, 3], 2) spray cooling [4], 3) micro-jet cooling [5], 4) cooling by falling liquid films [6-7], and 5) cooling by evaporation of a thin liquid film shear-driven in a channel [8-11]. Microchannel boiling is considered to be the optimal variant among those stated above due to its capability to maintain low operating temperatures with the least possible flow rates and minimum pumping requirements, compared to shear-driven films and spray cooling techniques.

Due to presence of the so called "hotspots" in microelectronics, i.e. small areas where heat flux could be several times higher than the average on a chip, conditions for the flow boiling on a localized heat source could be achieved. Flow boiling on localized heat sources is not well studied unlike the conventional flow boiling in channels with uniform heating. Papers on the stated problem have appeared recently [12, 13], however, they lack high speed visualization of boiling process, which is important to understand all circumstances of boiling on localized heat sources. Bubble dynamics may play an important role in boiling on localized heat sources and has to be studied thoroughly. As shown in [14] the dynamics of vapour bubbles for confined growth, which occurs in microchannels, differs significantly from the bubble dynamics during flow boiling in macrochannels. This raises the question...
of whether similar effects will appear for the bubble growth in flat microchannels, i.e. where the channel width is several times larger than the channel height.

Currently, there is a severe lack of experimental data on bubble growth in microchannels obtained with the recording speed of above 100 000 frames per second. These data are crucial for understanding the flow boiling in such confined spaces.

2. Experimental setup

Investigations are conducted on the experimental setup shown in Fig. 1. The experimental setup includes the following components: test section, liquid supply and thermal stabilization circuit, and the optical system consists of high-speed camera and microscope lens with high spatial resolution.

![Figure 1. Scheme of experimental setup. 1 – pump Ismatec Reglo-ZS, 2, 8 – plate heat exchanger HXP-193, 3 – flow meter Titan Atrato Ultrasonic, 4 – working area, 5 – pressure sensor WIKA P-30, 6 – tank with working fluid, 7 – circulation pump Lowara D5, 9 – circulation circuit of IT SB RAS, 10 – thermostat Huber MPC K6.](image)

The working liquid was supplied to the test section by means of adjustable Ismatec Reglo-z120 gear pump and the flow rate was measured by Atrato Ultrasonic flowmeter. The ultra-pure MilliQ water was used as the working fluid and it was thermally stabilized to the required temperature by passing through the plate heat exchanger where the required temperature was maintained with the aid of Huber MPC-K6 thermostat (see Fig. 1). The working fluid temperature was set to 26 °C and was controlled by thermocouple at the test section inlet. The divergence of the temperature of the working liquid from the
required 26 °C during the experiments did not exceed ± 0.5 °C. The experiments were carried out under atmospheric pressure. Pressure sensors at the inlet and outlet of the channel were installed to monitor pressure drop during experiments. The pressure drop along the channel did not exceed 0.2 Bar.

The longitudinal cross-section of test section is shown on Fig. 2. The test section includes a flat stainless-steel plate with a flush-mounted heater made from copper with a square head of 1 × 1 cm which serves as the working surface. The heat is electrically produced by means of a nichrome wire which is wrapped around a copper. The design of the heater provides close-to-constant temperature distribution on the working surface. The transparent glass serves as a top wall of the channel enabling the direct control of the boiling process. The desired channel height is created by placing changeable PTFE inserts with desired thickness. PTFE inserts also serve as side walls of the channel. The height of the channel H is measured by Micro-Epsilon IFC2451 confocal system and equals 0.6 mm, and the unevenness of the channel height along the flow direction is below 5%. The width of the channel is 34 mm, i.e. 3.4 times the width of the copper working surface. The working surface (stainless steel plate and the upper surface of copper head of the heater) is roughly polished. The root mean square (RMS) surface roughness is found to be 0.5 µm and is measured by means of an atomic force microscope. The heat flux is determined using thermocouples inserted into the test section (for more details see [15]).

![Figure 2. Schematic of the test section.](image)

Visualization of the bubble growth on the heater surface during boiling was carried out using a high-speed camera FASTCAM SA 5. The speed of shooting varied from 300 000 frames per second at the resolution of 256x64 pixels to 775 000 frames per second at the resolution of 128x24 pixels. The camera was equipped with an optical system of high spatial resolution (2.8 µm per 1 pixel of the camera sensor). Nikon SB-800 flash was used as a light source which provided a sufficient level of illumination for 2.5 ms. The distance from the upper edge of the heater to the center of the field of the camera view was about 4 mm.

### 3. Experimental results

With the aid of high-speed visualization, a top view video of the nucleate flow boiling in the channel was recorded. The diameter of the vapor bubble was measured frame by frame using the ImageJ software. On each frame with the bubble, a set of points was placed manually to mark the boundary of the bubble. These points were used to approximate the circle whose diameter was the diameter of the bubble. The image of typical bubble evolution obtained with the frame rate of 300 000 fps (one frame every 3.33 μs) is presented in Fig. 3. Raw bubble growth data obtained with frame rates of 300 000 and
775 000 fps is presented in Fig. 4. Zero of bubble growth incipience time is chosen on the frame before the first frame with a bubble.

**Figure 3.** Evolution of a vapour bubble (top view). $h = 0.6$ mm, $T_{\text{wall}} = 135^\circ$C, $G_{\text{liq}} = 125$ kg/m$^2$s, shooting speed of 300,000 fps (the interval between frames of 3.33 $\mu$s).

The maximum diameter of a bubble on the film is 407 $\mu$m.

**Figure 4.** The vapour bubble growth dynamics in the channel with the height of 0.6 mm. Symbols with filling – bubbles recorded at a speed of 300,000 fps, open symbols – at 775,000 fps. Zero of time is chosen on the frame before bubble appearance.
The obtained data on boiling in the flat minichannel with the height of 0.6 mm is processed by the method suggested in [16]. In this method, the correlation formula for initial bubble growth stage under given experimental conditions is derived. The correlation formula is based on the data obtained with the maximum possible recording speed, in our case 775 000 fps, which allows us to correctly determine the initial growth time for bubbles recorded with lesser camera speeds.

Experimental conditions were $T_{\text{wall}} = 135 – 136 ^\circ$C, heat flux varied in range of 125 – 168 W/cm$^2$, $\text{Re}=103$ (125 kg/m$^2$s), and liquid temperature at channel inlet was 25 °C. Given experimental conditions result in Jacob number $Ja = 106$. The correlation formula for initial vapour bubble growth under given experimental conditions was found to be:

$$D [\mu m] = 6894 \cdot t^{0.85} [ms]$$

where D is the bubble diameter and t is the bubble life time. Using the above correlation, zero for bubble growth incipience time was found for data obtained with recording speed of 300 000 fps, presented in Fig. 5.

![Figure 5. The vapour bubble growth dynamics in the channel with the height of 0.6 mm. Symbols with filling - bubbles recorded at a speed of 300,000 fps, and open symbols – at 775,000 fps.](image)

As can be seen from Fig. 5, the bubble growth data is in good agreement with Mikic-Rohsenow [17] correlation formula during the late stage of the growth process. At the late stage, bubbles approach Yagov-Labuntsov [18] growth correlation. Both correlation formulas were considered for the case of bubble growth on a heated wall. The agreement between the data and correlations in a 0.6 mm high channel is worse than in a similar channel with the height of 1 mm [16,19]. This could be explained as follows: in a 0.6 mm high channel the bubble growth is constrained by channel walls more significantly than in a 1 mm channel. This effect in channels with uniform heating is known as confined bubble...
growth [14]. It should be noticed, that both correlation dependences stated above do not take into account the effect of channel walls on the characteristics of bubble growth.

Conclusions
The obtained results on the bubble dynamics are in worse agreement with correlations well-known from the literature than for a 1 mm channel. This may be explained by the constraint of the bubble growth by channel walls. Further investigations in channels with lower height are necessary. The obtained data show that the bubble diameter can reach the channel height in about 0.1 ms, which can lead to heat transfer crisis in channels with local heating.

Acknowledgments
The study was performed under the support of Russian Foundation for Basic Research (Grant No. 19-08-01235).

References
[1] International Roadmap for Devices and Systems 2020 Institute of Electrical and Electronics Engineers
[2] Thome J 2004 International Journal of Heat and Fluid Flow 25
[3] Zaitsev D, Tkachenko E, Belosludtsev V, Kreta A, Kabov O 2018 Journal of Physics: Conference Series 1105 012142
[4] Kim J 2007 International Journal of Heat and Fluid Flow 28
[5] Robinson J, Kempers R, Colenbrander J, Bushnell N, Chen R 2018 Applied Thermal Engineering 136
[6] Chinnov E A, Kabov O A, Muzykantov A V, Zaitsev D V 2001 International Journal of Heat and Technology 19 31–44
[7] Zaitsev D V, Semenov A A, Kabov O A 2016 Thermophysics and Aeromechanics 23 625–8
[8] Zaitsev D V, Rodionov D A, Kabov O A 2009 Technical Physics Letters 35 680–2
[9] Kabov O A, Zaitsev D V 2009 Multiphase Science and Technology 21 249–66
[10] Tkachenko E, Zaitsev D 2016 MATEC Web of Conferences 72 01114
[11] Zaitsev D, Tkachenko E and Kabov O 2017 EPJ Web of Conferences 159 0054
[12] Palko J, Lee H, Zhang C 2017 Advanced Functional Materials 27(45) 1703265
[13] Nasr M, Green C, Kottke P 2017 International Journal of Heat and Mass Transfer 108 1702–13
[14] Yin L, Jia L 2016 International Journal of Heat and Mass Transfer 98 114–23
[15] Zaitsev D V, Tkachenko E M 2019 Journal of Physics: Conference Series 1369 012058
[16] Belosludtsev V, Zaitsev D 2020 AIP Conference Proceedings 2212 020011
[17] Mikic B, Rohsenow W and Griffith P 1970 International Journal of Heat and Mass Transfer 13(4) 657–66
[18] Labuntsov D 2000 Physical fundamentals of energy. Selected works on heat transfer, hydrodynamics, thermodynamics (Moscow MEI) (in Russian)
[19] Belosludtsev V 2019 Journal of Physics Conference Series 1369:012059