Vapour bubble dynamics in a flat mimi-channel under intense heating

V V Belosludtsev\textsuperscript{1,2}
\textsuperscript{1}Kutateladze Institute of Thermophysics SB RAS, 1, Lavrentiev Ave, Novosibirsk, 630090, Russia
\textsuperscript{2}Novosibirsk State University, 2, Pirogova str., Novosibirsk, 630090, Russia

E-mail: v.belosludtsev@g.nsu.ru

Abstract. Investigation of subcooled nucleate boiling in minichannels was conducted with high speed recording optical system also equipped with high spatial resolution optics. Obtained data on the bubble dynamics is in good agreement with well-known correlations from the literature. The final stage of bubble dynamics is in good agreement with the Labuntsov correlation for spherical vapor bubble growth on a heated wall.

1. Introduction

The rapid development and miniaturization of computational tools, in particular, the use of three-dimensional chip packages, as well as extreme heterogeneity of heat flux on the electronic component, for example, a computer chip, poses new scientific tasks for developers and researchers [1, 2]. The local heat flux in certain areas of the chip of about 0.1-2 mm in size (the so called “Hot spots”) can exceed the average heat flux density on the chip by more than an order of magnitude and can equal 1 kW/cm\textsuperscript{2} and more, which puts the task of studying heat removal of high and simultaneously uneven heat fluxes.

There are four well known methods of removing ultra high heat fluxes from localized heat sources: 1) boiling in mini and micro-channels [3], 2) spray cooling [4], 3) micro-jet cooling [5], and 4) evaporation of shear-driven thin liquid film in a channel [2,6,7]. Boiling in mini- and micro-channels is considered very promising for cooling in high heat generation systems, especially in future’s 3D stacked microelectronics. Those type of systems is capable to cool high heat fluxes with minimum required flow rate of the working fluid and maintaining low temperature of the channel walls [8]. Likely, microchannels is the most effective solution for thermal management of future microelectronics with 3D stacked architectures.

In the majority of studies on flow boiling in mini- and microchannels known from literature the vapour bubbles was studied at relatively low heat fluxes and the majority of authors studied dynamics of rather large bubbles - millimetre in size and larger (see for example [9]). In the recent work of [10] there have been observed two previously unknown stages of vapour bubble growth and the first stage was characterized by growth with rate exceeded 12.5 m/s and life time less than 10 μs, which means those type of bubbles can lead to blockage of microchannel. Data about bubble dynamics in microscale channels is quite limited and will be crucial for design of microchannel cooling systems.

The main intention of this paper is to study the subcooled flow boiling in a flat mini-channel under localized heating of the wall. Investigation of microbubble dynamics during subcooled nucleate
boiling was conducted with high-speed recording optical system also equipped with high spatial resolution optics.

2. Experimental setup

Research were conducted on the experimental facility shown in Fig. 1. The facility consisted of the following: test section, liquid loop, thermal stabilization circuit, optical system with high speed camera equipped with high spatial resolution optics. Facility also equipped with automatic data acquisition system.

Fig. 1. Schematic of the experimental facility.

Milli-Q degassed ultra-pure water which was used as working liquid was supplied to the test section by the Ismatec Reglo Z-183 gear pump. The liquid flow rate was controlled manually by means of the pump in the range from 4.2 to 420 ml/min. The working liquid was thermally stabilized in a plate heat exchanger with the aid of a thermostat to the temperature of 25 °C and after that it was supplied to the test section. The temperature of the water at the inlet to the test section was controlled by a thermocouple integrated into the test section. The deviation of the temperature of the working liquid at the inlet was not exceeding ± 0.4 °C during the experiments. Pressure at the inlet and outlet of the channel was measured by pressure sensors, experiments were carried out under normal pressure. The pressure drop along the channel of test section did not exceed 0.2 Bar.

The test section consisted of a thin flat plate made of stainless steel with a copper heater rod having a square head of 1 × 1 cm serving as a heater surface (Fig. 1), heater and plate was grinded to form uniformly flat plate. Joule heat was generated by electricity supplied to a nichrome wire which was wrapped around heater rod. The design of the heater provides constant temperature on the surface of the rod, T_w=const (as confirmed by thermocouple measurements). The top wall of test section is made from enlightened glass. The height of a channel is adjusted by placing changeable inserts between the working substrate and the glass top. 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 roughly polished and the morphology of the working surface was analyzed by an atomic force microscope. The root mean square (RMS) surface roughness was found to be 0.79 µm. Dynamics of the process of boiling on the heater was visualized by a high-speed camera FASTCAM SA1.1 made by Photron. The frame rate was varying from 5400 frames per second at the resolution of 1024x1024 pixels to 100000 frames per second at the resolution of 300x128 pixels. Optical system
with high spatial resolution (up to 2.5 µm per 1 pixel of the camera sensor) was equipped on the camera. The distance from the upper edge of the heater to the center of the field of view of the camera view is about 1.5 mm.

3. Results

Data on the nucleate flow boiling in the channel was obtained by high-speed visualization. Images obtained from top view was processed with help of ImageJ software. Image of typical bubble evolution obtained with frame rate of 54,000 fps (one frame every 18.5 μs) are presented in Fig. 2. The zero time of bubble growth is taken at the very first frame when bubble is observed. Because of existence of dissolved gas in the liquid an additional nucleus can be observed near pure vapour bubble shown in Fig. 2.

![Fig. 2. Evolution of typical vapour bubble. Interval between frames is 18.5 µs.](image)

Our data on boiling in flat minichannel with height of 1 mm is presented in color in Fig. 3. Data has been compared with data from literature obtained for water at atmospheric pressure, see Table 1 for exact conditions. Data has been compared with Labuntsov [11] equation for spherical bubble growth on the heated wall and Mikic-Rohsenow [12] equation for spherical and hemispherical bubble on a heated wall. At the final stage of growth, dynamics of our vapor bubbles is in good agreement with the Labuntsov [11] correlation dependence for vapor bubble growth on a heated wall, while the
initial growth stage is satisfactorily described by the Mikic-Rohsenow correlation for hemispherical bubble on a heated wall [12].

| Author | Experimental setup | Conditions |
|--------|---------------------|------------|
| [9]    | Stainless steel tube d=12.7 mm; L=48 mm | p= 1.05 atm, G=78-800 kg/(m⋅s), ΔT_{sub} =20 – 30 K, q = 30 – 120 W/cm² |
| [10]   | Silicon substrate with gold plated spheres d= 45 nm | p= 1 atm, pool boiling, ΔT_{sub} = 75 K, q = 80 – 100 W/cm² |
| [13]   | Stainless steel tube d = 10 mm inside of glass tube with d = 30 mm, L = 100 mm | p= 1 atm, G=100 kg/(m⋅s), ΔT_{sub} = 20, q = 70 W/cm² |
| [14]   |                           | p= 1 atm, pool boiling, ΔT_{sup} = 38 K |

Table 1. Data on the dynamics of vapour bubbles obtained for water at atmospheric pressure.

Fig. 3. Comparison of obtained data (for 11 bubbles) with correlations and data from the literature.
Since our bubbles is seen from top, we cannot know exact shape of our bubbles, perhaps, at the initial stage of intensive growth of the vapor bubble, due to the action of inertial forces of the liquid, the vapor bubble is hemispherical, as shown in [10]. The Jacob number used for both correlation formulas is 75, which corresponds to a heater wall temperature of 125 °C under the given experimental conditions. The good agreement between the experimental data of [10] (for semispherical bubbles) and the correlation formula of Labuntsov (for spherical bubbles) calculated for our experimental conditions is probably accidental, since the heating scheme in the experiment [10] is completely different and the Jacob number cannot be calculated, because the wall temperature is not measured in [10].

4. Conclusion

Boiling of subcooled water flow in a mini-channel under local heating was studied experimentally. Microbubble dynamics during subcooled flow boiling was studied with high-speed optical system with high spatial resolution. Obtained results on the bubble dynamics is in good agreement with correlations well-known from the literature. Obtained data show that in the case of 1 mm high channel the bubble can reach the upper wall of the channel in less than 1 ms, while in the case of 100 μm high channel it will reach the upper wall in about 10 μs, i.e. the use of cameras with speeds of at least 1 million fps is needed for investigation of bubble dynamics in microchannels.

The study was carried out under financial support of Russian Foundation for Basic Research (Grant No. 19-08-01235).

References

[1] Bar-Cohen A and Wang P 2009 Second International Conference on Micro/Nanoscale Heat and Mass Transfer 553–567
[2] Zaitsev D, Tkachenko E, and Kabov O 2017 EPJ Web of Conferences, 159, 00054.
[3] Thome J 2004 International Journal of Heat and Fluid Flow, 25.
[4] Kim J 2007 International Journal of Heat and Fluid Flow, 28.
[5] Robinson J, Kempters R, Colenbrander J, Bushnell N, Chen R 2018 Applied Thermal Engineering, 136.
[6] Kabov O A, Lyulin Yu V, Marchuk I V, and Zaitsev D V 2007 International Journal of Heat and Fluid Flow, 28, 103–12
[7] Tkachenko E, Zaitsev D 2016 MATEC Web of Conferences, 72, 01114
[8] Zaitsev D, Tkachenko E, Belosludtsev V, Kreta A, Kabov O 2018 Journal of Physics: Conference Series, 1105 (1), 012142
[9] Prodanovic V, Fraser D and Salcudean M 2002 International Journal of Multiphase Flow, 28, 119334
[10] Wang Y, Zaytsev M., The H, Eijkel J, Zandvliet H, Zhang X, Lohse, D. 2017 ACS nano, 11(2), 2045-2051
[11] Labuntsov D 2000 Physical fundamentals of energy. Selected works on heat transfer, hydrodynamics, thermodynamics (in Russian) Moscow MEI
[12] Mikic B, Rohsenow W and Griffith P 1970 International Journal of Heat and Mass Transfer 13(4) 657-666
[13] Akiyama M, and Tachihana F 1974 Bulletin of JSME, 17(104), 241-247
[14] Abdelmessih A 1969 Spherical bubble growth in a highly superheated liquid pool, Plenum Press