The dynamic of the water explosive vaporization on the flat microheater

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Abstract. The dynamic of explosive vaporization of the water on the multilayer thin-film resistor with the size of 100×110 μm has been investigated. An original optical method based on measuring of laser intensity reflected from resistor surface was used. The characteristics of the initial stage of the explosive vaporization were obtained. The dependence of the boiling temperature on the temperature growth rate and the dependence of boiling time on the effective heat flux were defined. The lifetime of the main vapour bubble and the satellite bubble were estimated.

1. Introduction
Studies of heat and mass transfer with phase change in microfluidic systems are developing rapidly. This is due to a growing interest in the microelectromechanical (MEMS) systems. The MEMS technology makes it possible to obtain extremely high temperatures, vapor phase nucleation and bubble dynamics on the microheater.

Investigations of the explosive boiling-up on the flat microheater were performed in [1]. Micro-optical method for monitoring of the initial stage of explosive boiling in n-hexane was described in [2]. Micro explosive bubbles actuated by thermal pulses are widely applied on driving fluids in microchannels [3]. The characteristics of water explosive vaporization due to the high-impact thermal pulse from multilayer microheater with external submicron silicon carbide layer were obtained in [4]. Explosive boiling-up at the microscale is generated by rapid heating of the liquid on the microheater to a temperature close to the boundary of the thermodynamic stability of the liquid. The explosive vaporization of a liquid is a physical process in which the vapor phase is formed with the maximum rate. The aim of this work is the experimental study of the initial stage of explosive boiling-up of water with additives of silicon dioxide nanoparticles on the rectangular microheater manufactured by Hewlett Packard technology with the size of 100x110 μm. At the initial stage of this work, water without nanoparticle additives was used as the base liquid. The optical method was used to investigate the explosive vaporization of a liquid, based on measuring the intensity of laser radiation reflected from the surface of the microheater.

2. Experimental equipment and methods
The experimental setup for studying the dynamics of explosive vaporization on the microheater is shown in figure 1 (a). The microheater is a multilayer thin-film resistor with the size of 100x110 μm [5], figure 1 (b). The microheater (1) is immersed in the working fluid (2), and its surface
is lit by laser (3). The initial temperature of the liquid was determined before the experiment started and ranged from 18 to 21°C, the experiments were conducted at atmospheric pressure. The single rectangular current pulse is supplied to the microheater from the 214B Hewlett Packard pulse generator. Each pulse has sufficient duration for the explosive vaporization of liquid near the surface of the microheater. Effective heat flux is determined as supplied heat is divided by resistor surface area. The initial stage of explosive vaporization was studied using the optical registration, based on measuring the intensity of the laser beam (3) reflected from the mirrored surface of the microheater (1). The reflected laser beam from the heater enters the microscope (4). The diaphragm (5) selects an area with the microheater surface. The intensity of the laser beam is measured by the photodiode (6). The signal from the photodiode is registered with the high-speed ADC (7). The integral coefficient of the laser light reflection begins to decrease during the appearance of microbubbles on the microheater. The signal from the photodetector provides the information about the history of the heater surface coverage by vapor bubbles. This method is used to trace the dynamics of the vapor filling of the surface on the microheater, depending on the effective heat flux $q_{\text{eff}}$

The process of the water explosive vaporization was visualized with the help of video camera. The photograph of the heater surface is shown in figure 1 (c) for the water explosive vaporization after 4.5 μs the start of heating.

3. Experimental results

Figure 2 (a, b, c) shows the intensity of the reflected laser beam depending on the time during the explosive vaporization of water on the microheater 100x110 μm. It corresponds to dynamics of the surface coverage by the bubbles during the explosive vaporization. The dark line shows the intensity dependence of reflected light according to the time during the explosive vaporization. The normalized signal from the generator is also shown in figure 2 by a thin line. The zero time in figure 2 corresponds to the start of heat pulse from the generator.

Figure 2 (a) shows the intensity of reflected laser beam depending on the time during the explosive vaporization of the water on the microheater with the size 100x110 μm for the effective heat flux $q_{\text{eff}} = 508.17$ MW/m², the growth rate of temperature $\frac{dT}{dt} = 40.17$ MK/s and duration of the heating pulse $t = 5.238$ μs. Figure 2 (b) shows the intensity of reflected laser beam depending on the time for the effective heat flux $q_{\text{eff}} = 1145.2$ MW/m², the growth rate of temperature $\frac{dT}{dt} = 146.9$ MK/s and duration of the heating pulse $t = 2.098$ μs. Figure 2 (c) shows the intensity of reflected laser beam depending on the time for the effective heat flux $q_{\text{eff}} = 2181.6$ MW/m², the growth rate of temperature $\frac{dT}{dt} = 277.7$ MK/s and duration of the heating pulse $t = 1.162$ μs. The oscillations in the signal are associated with an increase in the number of bubbles for the high temperature growth rate.
The temperature to boil 2 μs, the value of $t_{\text{boil}}$ 1.162, $dT/dt$ 5.238 μs. The time from the beginning of the pulse from the generator to the appearance of the first bubbles on the microheater is defined as the time of initiation of explosive vaporization $t_{\text{ini}}$. The dependence of the boiling time $t_{\text{boil}}$ and the time of initiation of explosive vaporization as a function of the heat flux were determined for the clean water, figure 3 (b). The value of $t_{\text{boil}}$ varied from 16 to 12 μs, the value of $t_{\text{ini}}$ varied from 9 to 0.8 μs on the microheater with the size of 100x110 μm.

The heat conduction equation was used to find heat flow from the microheater to the liquid (water) for a multilayer heater. The temperature of the liquid, the temperature growth rate and the heat flux transferred to the liquid was determined depending on the heat power released on the heating layer. Thermal conductivity and heat capacity of the layers were taken from literature data. Thermal conductivity and heat capacity of the layers were taken from literature data. The dotted line on figure 3 (a) for the water on the microheater with size 100x110 μm. The dotted line on figure 3 (a) presents the solution of the equation $T_{\text{lim}}/T_{\text{sat}} = 0.905 + 0.095 \times (T_{\text{sat}}/T_{\text{cr}})^3$ for limiting superheating of liquid based on the data of [6]. The solid line shows the spinodal line calculated according to [7].

The time between the beginning of explosive vaporization and the moment of collapse of the first vapor bubble is defined as the time of boiling $t_{\text{boil}}$. The time from the beginning of the pulse from the generator to the appearance of the first bubbles on the microheater is defined as the time of initiation of explosive vaporization $t_{\text{ini}}$. The dependence of the boiling time $t_{\text{boil}}$ and the time of initiation of explosive vaporization as a function of the heat flux were determined for the clean water, figure 3 (b).

The intensity of the reflected laser beam depending on the time: (a) $q_{\text{eff}} = 508.17$ MW/m$^2$, $dT/dt = 40.17$ MK/s, $t = 5.238$ μs, (b) $q_{\text{eff}} = 1145.2$ MW/m$^2$, $dT/dt = 146.9$ MK/s, $t = 2.098$ μs, (b) $q_{\text{eff}} = 2181.6$ MW/m$^2$, $dT/dt = 277.7$ MK/s, $t = 1.162$ μs.

The time from the beginning of the pulse from the generator to the appearance of the first bubbles on the microheater is defined as the time of initiation of explosive vaporization $t_{\text{ini}}$. The dependence of the boiling time $t_{\text{boil}}$ and the time of initiation of explosive vaporization as a function of the heat flux were determined for the clean water, figure 3 (b). The value of $t_{\text{boil}}$ varied from 16 to 12 μs, the value of $t_{\text{ini}}$ varied from 9 to 0.8 μs on the microheater with the size of 100x110 μm.
4. Conclusions

The analysis of the explosive vaporization dynamics for the clean water without silicon dioxide nanoparticles on the microheater with the dimension of 100x110 μm is presented. The optical method based on a change in the intensity of the laser beam mirrored from the surface of the microheater made it possible to study the dynamic of the initial stage of the explosive vaporization of the liquid. Using this method, experimental data on the dynamics of filling the surface of the heater with vapor bubbles, the dependence of the boiling time and the lifetime of the main bubble on the effective density of the heat flux was determined. The dependence of temperature of the explosive vaporization initiation on the temperature growth rate was determined.

Acknowledgement

This work performed in the Kutateladze Institute of Thermophysics SB RAS by the grant KPFI of the SB RAS Interdisciplinary integration studies, project 5.3.

References

[1] Hong Y et al 2004 Experimental study of bubble dynamics on a micro heater induced by pulse heating J. Heat Transfer 126(2) 259–71
[2] Gurashkin A L et al 2012 Communication: high speed optical investigations of a character of boiling-up onset Journal of Chemical Physics 021102
[3] Okuyama K et al 2005 Pumping action by boiling propagation in a microchannel Microscale Thermophys. Eng. 9(2) 119–35
[4] Kuznetsov V V and Kozulin I A 2010 Explosive vaporization of a water layer on a flat microheater J. Eng. Thermophysics 19(2) 102–9
[5] Bhaskar E V and Aden J S 1985 Development of the thin-film structure for the ThinkJet printhead Hewlett-Packard Journal 36(5) 27–33
[6] Skripov V P 1974 Metastable Liquids (John Wiley & Sons)
[7] Skripov P V and Skripov A P 2010 The phenomenon of superheat of liquids: in memory of Vladimir P Skripov Int. J. Thermophys. 31(4–5) 816–30