Explosive vaporization of two- and three component liquid mixtures on microheater

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Abstract. The explosive vaporization of two-component mixtures of ethanol-water and three-component mixtures of acetone-ethanol-water during pulse thermal loads on the microheater during isobaric heating has been investigated. Microheater fabricated using MEMS technology presents the multilayer thin-film structure with the central Ta-Al layer heated by pulse electric current. The optical method based on measuring the laser intensity reflected from resistor surface recorded the characteristics of explosive vaporization. The dependence of the temperature of nucleation and the time of explosive vaporization on the rate of temperature growth and heat flux density are obtained.

1. Introduction

The investigations of the explosive vaporization of multicomponent liquid mixtures on the microheater are important for the design of microelectromechanical systems (MEMS), based on the explosive vaporization. Despite the fact that the explosive vaporization of one-component liquids for this condition is well studied [1 - 3], the presence of volatile component in binary mixture can considerably reduce the temperature of nucleation [4]. Experimental investigations of the explosive vaporization in hydrocarbon mixtures were conducted in [5, 6] and explosive vaporization of alcohol-water mixture was studied in [7, 8]. It was obtained that the nucleation temperature for water-methanol mixtures depends on the methanol concentration and, as it increases, the nucleation temperature decreases [8]. The aim of the current study is the experimental investigation of the characteristics of explosive vaporization of two-component mixtures of ethanol-water and three-component mixtures of acetone-ethanol-water that have significantly different critical temperatures. The experiments are performed at pulse thermal loads in isobaric conditions using the microheater manufactured by Hewlett Packard MEMS technology. The optical method [9] based on measuring the variation of the intensity of laser beam reflected from microheater surface during nucleation is applied to study the initial stage of the explosive vaporization of multicomponent liquid mixtures.

2. Experimental equipment and methods

When conducting experiments, the multi-layer heaters manufactured by the technology of microelectromechanical systems are used to provide for the multi-pulse measurements without the microheater destruction. In the tests, the microheaters manufactured by Hewlett-Packard technology [10] with the external layer made of carbide silicon and nanostructured tantalum are used. The experimental setup for studying the explosive vaporization of two-component mixtures of ethanol-
water and three-component mixtures of acetone-ethanol-water is shown in figure 1 (a). The multilayer thin-film heater with the size of 100x110 μm has an external layer made of carbide silicon and the heater with the size of 61x66 μm has the external layer made of nanostructured tantalum. The morphology of the outer layer of the microheater with the size of 100x110 μm obtained using atomic force microscopy is shown in figure 1 (b). The surface roughness of this heater in the area from 0 to 1 μm is \( R_z = 2.72 \) nm. During the experiments, the microchip with the heater (1) is immersed in the cuvette with the liquid mixture (2), shown in figure 1 (a). The initial temperature of the liquid is measured before the experiments and varies from 17.8 to 22.2 °C. The experiments are performed at atmospheric pressure in the isobaric conditions. Single rectangular electric current pulses are supplied to the resistor layer of the microheater from electric pulse generator. Each pulse has the duration sufficient for generation of the explosive boiling on a heater surface.

To study explosive vaporization, the optical technique for detecting explosive vaporization is used. This technique is based on measuring the intensity of laser beam (3) reflected from the area of a phase change in microheater (1). After reflection, the laser beam is sent into the microscope (4) and the region with the microheater is highlighted using the diaphragm (5). The radiation intensity of reflected laser beam is recorded by photodiode (6) and registered by high-speed ADC (7). When microbubbles occur, the integral coefficient of specular reflection begins to fall and the signal from the photodiode registers the dynamics of the explosive vaporization depending on effective heat flux on the heater surface. The effective heat flux \( q_{\text{eff}} \) is determined as the total amount of heat released per unit time divided to the heater area. The heat flux to the liquid \( q_w \) and the rate of the liquid temperature growth on the heater surface \( \frac{dT}{dt} \) are determined by numerically solving the Fourier equation for the multilayer heater taking into account the heat released in a resistor layer. The thermal conductivity and specific heat of the layers are taken from literature data. The physical properties of two- and three-component mixtures are calculated considering the mass and mole fractions of the components using the equations for heat conductivity, heat capacity and density from [11].

3. Experimental results

The homogeneous nucleation of the liquid mixtures becomes dominant at high growth rates of the liquid temperature. The experiments with pulse ultrahigh thermal loads are conducted to obtain the characteristics of explosive vaporization of liquid mixtures with various mass fraction of volatile components. Figure 2 (a) shows the intensity of reflected laser beam depending on time for water at \( q_{\text{eff}} = 398.6 \) MW/m². A thin line shows the normalized electric current supplied to the resistor layer depending on time. The bold line shows variation of the intensity of reflected laser beam depending on time when the explosive vaporization occurs. Initial growth of the signal from photodiode is caused by heating of the liquid near heater surface up to point B. The signal from the photodiode is normalized so that the dimensional intensity at start time equals to unity and signal start...
Figure 2. Intensity of reflected laser beam depending on time for water at $q_{\text{eff}} = 398.6$ MW/m$^2$ (a), ethanol-water with mass fraction of 0.6 and 0.4 at $q_{\text{eff}} = 303.8$ MW/m$^2$ (b), acetone-ethanol-water with mass fraction of 0.5, 0.4, and 0.1 at $q_{\text{eff}} = 282.8$ MW/m$^2$ (c).

... coincides with the time of the heating pulse from the generator. When explosive vaporization occurs, the intensity of reflected laser beam drops sharply corresponding to the increase in the number and size of the bubbles between points B to C. The stage of the condensation of combined bubble ends at point B with subsequent growth and collapse of the satellite bubble in point E.

The characteristics of the explosive vaporization of the two-component ethanol-water mixture with the mass fraction of 0.6 and 0.4, respectively, is shown in figure 2 (b) for $q_{\text{eff}} = 303.8$ MW/m$^2$. The increase of the duration of initial vaporization stage (stage B-C) compared with less water mass fraction and decrease in the size of the satellite bubble are obtained.

The dependence of the intensity of reflected laser beam on time during explosive vaporization of three-component mixture of acetone-ethanol-water with the mass fraction of 0.5, 0.4, and 0.1, respectively, is shown in figure 2 (c) for $q_{\text{eff}} = 282.8$ MW/m$^2$. As it is shown in this picture, increasing the acetone mass fraction leads to significant decrease in the duration of initial stage of explosive vaporization (stage B-C) and increase in the size of the satellite bubble.

The dependence of the temperature of nucleation on the rate of temperature growth for acetone-ethanol-water mixture with mass fraction of 0.5, 0.4, 0.1, respectively, is shown in figure 3 (a).

(a)

(b)
To determine the nucleation temperature, the measured time of nucleation and numerical calculations of the temperature growth for liquid mixture are used considering the dependence of the physical properties of mixtures on the mass fractions of the components. The lines in figure 3 (a) show the calculations of the temperatures of nucleation assuming linear dependence of the temperature of limiting superheat on molar concentration of the components. For water and ethanol, the correlation [12] based on experimental data [13] is used to determine the temperatures of limit superheat.

The dependence of the total explosive vaporization time (stages B-D) on effective heat flux and mass fractions of the volatile components for three-component mixture of acetone-ethanol-water is shown in figure 3 (b). As it is seen, the non-monotonic dependence of the nucleation time on mass fraction is observed for studied mixtures.

Conclusions
The results of the present study have been obtained using the optical method aimed at resolving the explosive vaporization characteristics at times of the order of tens nanoseconds. It allows finding new features of the explosive vaporization of two-component mixtures of ethanol-water and three-component mixtures of acetone-ethanol-water that have significantly different critical temperatures. For the two-component ethanol-water mixture, the increase of the duration of initial vaporization stage and the decrease in the size of satellite bubble with an increase in the water mass fraction have been obtained. For the three-component mixture of acetone-ethanol-water, an increase in the acetone mass fraction leads to significant decrease in the duration of initial stage of explosive vaporization and an increase in the size of the satellite bubble. It has been obtained that the temperature of explosive vaporization for the ternary mixture having one polar component not fully corresponds to the linear dependence on the molar concentration of volatile components. The results obtained reveal the influence of the mass fraction of volatile components in two-component and three-component mixtures on the characteristics of explosive vaporization, which can be used to control this process by changing mass fraction of the components and effective heat flux density in the case of multi-component mixtures.

Acknowledgement
The research was carried out in the IT SB RAS with the support of the Russian Science Foundation grant (project No. 16-19-10519-C).

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