The dynamics of explosive vaporization of a two-component liquid mixture

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Abstract. The dynamics of explosive vaporization of the 2-propanol/water and ethanol/water mixtures on the multilayer thin-film resistor with the size of 100×110 µm has been investigated. An original optical method based on measuring the laser intensity reflected from resistor surface was used. The characteristics of the initial stage of the explosive vaporization of two-component mixtures were obtained. The dependence of the temperature of explosive vaporization on the rate of temperature growth and the dependence of the boiling time on effective heat flux were defined.

1. Introduction

The studies of liquids superheating have contributed to the development of several new technologies, and they have the potential of revolutionizing the design of thermal micro-devices including microelectromechanical systems (MEMS), based on the explosive boiling of a liquid. Despite the fact that the characteristics of explosive boiling of one-component liquids in microheaters are well studied [1 - 3], the presence in the mixture of the second component can significantly change the temperature of the explosive phase transition [4]. Experimental study of the homogeneous nucleation in hydrocarbon mixtures was done in [5, 6], at that, the study of nucleation in alcohol/water solution has received much less attention [7, 8]. The bubble nucleation temperature of water/methanol mixtures was measured using the fast transient process of thermal ink-jet printer technology in [8]. It was shown that as methanol concentration increases, the nucleation temperature decreases.

The aim of this work is an experimental study of the initial stage of explosive vaporization of 2-propanol/water and ethanol/water mixtures on the rectangular microheater manufactured by Hewlett Packard technology with the size of 100x110 µm. The optical method is used to investigate the dynamics of explosive vaporization of a liquid, based on measuring the intensity of laser radiation reflected from the surface of the microheater [9].

2. Experimental equipment and methods

The experimental setup for studying the dynamics of explosive vaporization of alcohol/water mixture on the microheater is shown in Fig. 1a. The microheater is a multilayer thin-film resistor with the size of 100x110 µm [10]. The roughness of the outer layer of the microheater was measured by atomic force microscopy, see Fig. 1b, the surface roughness in the area from 0 to 1 µm is Ra = 1.19 nm, and RMS = 1.53 nm. The microheater (1) is immersed in the working liquid (2), and its surface is illuminated by laser (3). The initial temperature of the liquid was determined before the experiment.
and ranged from 18 to 23 °C, and the experiments were conducted at atmospheric pressure. The single rectangular current pulse is supplied to the microheater from the 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 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 light reflection begins to decrease during the appearance of microbubbles on the microheater. The signal from the photodetector provides 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 \( q_{\text{eff}} \) on the microheater.

The process of water explosive vaporization was visualized with the help of the video camera. The photograph of the heater surface at 1.8 \( \mu \text{s} \) after the start of the heating is shown in Fig.1c for the explosive vaporization of ethanol at \( q_{\text{eff}}=522 \text{ Mw/m}^2 \).

![Figure 1](image1.png)

**Figure 1.** Experimental setup (a), morphology of microheater surface (b), photo of explosive vaporization of ethanol at 1.8 \( \mu \text{s} \) after start of heating, \( q_{\text{eff}}=522 \text{ Mw/m}^2 \) (c).

3. Experimental results
The experiments were conducted to obtain the characteristics of explosive vaporization of alcohol/water mixtures with various volume concentrations of alcohol \( c_0 \). Figure 2 (a) shows the

![Figure 2](image2.png)

**Figure 2.** Intensity of reflected laser beam depending on time: (a) water, \( q_{\text{eff}}=579 \text{ Mw/m}^2 \), \( \text{d}T/\text{d}t=51.9 \text{ MK/s} \); (b) ethanol, \( q_{\text{eff}}= 522 \text{ Mw/m}^2 \), \( \text{d}T/\text{d}t = 85.68 \text{ MK/s} \); (c) 60% 2-propanol/water, \( q_{\text{eff}}= 592 \text{ Mw/m}^2 \), \( \text{d}T/\text{d}t =52.3 \text{ MK/s} \).
intensity of the reflected laser beam depending on time for water at $q_{eff} = 579 \text{ Mw/m}^2$, $dT/dt = 51.9 \text{ MK/s}$. Here $J(t)/J_0$ is the intensity of the reflected laser beam $J(t)$ divided on the intensity of the reflected laser beam at the beginning of heating $J_0$. Figure 2 (b) shows the intensity of the reflected laser beam depending on time for ethanol at $q_{eff} = 522 \text{ Mw/m}^2$, $dT/dt = 85.68 \text{ MK/s}$. Figure 2 (c) shows the intensity of the reflected laser beam depending on time for 60% 2-propanol/water mixture, $q_{eff} = 523 \text{ Mw/m}^2$, $dT/dt = 52.3 \text{ MK/s}$. The oscillations in the signal are associated with an increase in the number of bubbles for the high-temperature growth rate. The thin line in Fig. 2 represents the normalized electric current from a generator; the thick line represents the dependence of the intensity of the reflected light as a function of time. It corresponds to dynamics of the surface coverage by the bubbles during the explosive vaporization.

Zero time in Fig. 2 corresponds to the start of the heat pulse. Stage A-B corresponds to liquid heating, stage B-C corresponds to the time of explosive vaporization, when microbubbles appear and grow up. The increasing of the intensity of the reflected laser beam during liquid heating (stage A-B) is caused by a change of the refractive index near the heater surface due to temperature growth. Stage C-D corresponds to the agglomeration of the microbubbles into the vapor cavity, and the cavity grows and collapse. After the cavity collapse, the existence of a satellite bubble is observed if the thermal energy accumulated during liquid heating is sufficient (stage D-E). The time interval B-E is defined as the duration of the explosive phase change $t_{boil}$, and the interval AB is defined as the heating time before the nucleation starts $t_{nuc}$. As it is seen, the time of explosive vaporization for water is considerably higher than that for alcohols, and the addition of 2-propanol to water decreases the time of total coverage of the heater surface by vapor phase, as it is shown in Fig. 2c.

In the experiments, the time of nucleation depending on effective heat flux is measured. The heat conduction equation for multilayer heater was solved to find the actual heat flux to the liquid, liquid temperature and rate of liquid temperature growth. Thermal conductivity and heat capacity of the layers were taken from literature data. The temperature of explosive vaporization depending on the temperature growth rate for 2-propanol/water mixture with different 2-propanol concentration is presented in Fig. 3a. In this figure, the experimental data are shown as points. And the lines, in the approximation of linear dependence on the molar concentration of a volatile component, show the calculation of the temperature of superheat limit according to the equation $T_{sat}/T_{cr} = 0.905 + 0.095 (T_{sat}/T_{cr})^8$ proposed in [11] using the experimental data [12]. Obviously, the temperature of superheat limit for the binary mixture having one polar component not corresponds to

![Figure 3](image-url)

**Figure 3.** Dependence of the temperature of on explosive vaporization rate of temperature growth: (a) 2-propanol/water, (b) ethanol/water.
the linear dependence on the molar concentration of low boiling component. The temperature of
initiation of the explosive vaporization depending on the temperature growth rate for ethanol/water
mixture with different ethanol concentration is presented in Fig. 3a. As it is seen, the water and alcohol
have a considerably different temperature of nucleation, and this temperature decreases with the
increase of alcohol content.

Conclusions
The results of the present study were obtained using an original optical technique, which allows
resolving processes at times of the order of ten nanoseconds during rapid phase change in
alcohol/water mixtures near the microheater surface. It allowed us to find new characteristics of the
explosive vaporization of 2-propanol/water mixture and ethanol/water mixture with different
centration of low boiling component. It has been obtained that the temperature of superheat limit
for the binary mixture that does not fully comply with the laws of Raul and Henry not correspond to
the linear dependence on the molar concentration of low boiling component.

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