Explosive vaporization of water-based nanofluid on a flat microheater

I A Kozulin$^{1,2}$, V V Kuznetsov$^{1,2}$

$^1$SB RAS, Institute of Thermophysics, Lavrentieva av. 1, Novosibirsk, 630090, Russia
$^2$Novosibirsk State University, Pirogova str. 1, Novosibirsk, 630090, Russia

E-mail: vladkuz@itp.nsc.ru

Abstract. The explosive vaporization of the nanofluid formed by water and SiO$_2$ nanoparticles on a heater with the size of 100×110 μm was studied. In experiments, the reflected optical signal produced by heater lighting using laser beam was measured. The patterns of the initial stage of the nanofluid explosive vaporization were obtained and the effect of nanoparticles on the nucleation temperature was discussed. The variation of the nucleation temperature and vaporization time depending on the temperature increase rate was defined.

1. Introduction
Investigations of the explosive vaporization of liquid on microscale are widespread recently due to needing in the design of MEMS systems for high technologies. The MEMS allows for obtaining high temperature increase rate and homogeneous nucleation using microheaters. The regimes of explosive vaporization of water were obtained in [1-3]. The initial stage of explosive vaporization of water on a rectangular heater with a small size was studied in [4]. The bubble formation around gold nanoparticles during pulsed heating was studied in [5]. It is well known that the explosive vaporization occurs when the superheat limit of the liquid is achieved. This work is aimed on the experimental investigation of the explosive vaporization of the nanofluid formed by water and SiO$_2$ nanoparticles on a heater with the size of 100×110 μm. To investigate the initial stage of the explosive vaporization, the reflected optical signal produced by heater lighting using the laser beam was measured that shows the microbubbles appearance.

2. Experimental equipment and methods
The experimental setup for investigation of the nanofluid explosive vaporization produced by the heater with a small size is shown in figure 1 (a). The multilayer thin-film heater with the size of 100x110 μm is shown in figure (b) was used in the experiments. This heater has external layer manufactured from silicon carbide. To supply stepwise current for a conductive layer of the heater, the pulse generator was used. The duration of the current pulse was selected so that it is sufficient to produce the explosive vaporization. The supplied heat divided by resistor surface area was used as the “effective” heat flux. The heater (1) was placed in the water or nanofluid (2), and the heater surface was lighting by a laser beam (3). The reflected optical signal was measured using the microscope (4), the photodiode (6) and high-speed ADC (7). The diaphragm (5) selects the area of the heater surface where the nucleation occurs and the reflected optical signal begins to go down due to microbubbles appearance. Therefore, the variation of the reflected optical signal corresponds to the dynamics of the
vapor bubbles appearance. This method was used for investigation of the patterns of initial stage of the vaporization depending on the effective heat flux $q_{\text{eff}}$ and liquid temperature increase rate. The initial liquid temperature of the liquid was supported in the range from 18 to 21 °C and the static pressure equals atmospheric pressure.

When preparing the nanofluid, the required amount of silica nanoparticles Aerosil 200 is added to the deionized water and vibrated in the ultrasonic bath for a long time. The volume concentration of nanoparticles in a liquid $c_0$ is determined using the density of water and amorphous silicon.

To find the flux transferred to liquid for a heater consists of four layers produced from different materials, the Fourier equation was solved numerically. The liquid temperature, liquid temperature increase rate and heat flux were obtained depending on time for given heat released in the conductive layer. The literature data were used to select the thermal conductivity and heat capacity of the heater layers.

3. Experimental results
The variation of the dimensionless reflected optical signal in time during explosive vaporization of deionized water for (a) $q_{\text{eff}} = 37.6$ kW/cm$^2$, $dT_{\text{liq}}/dt = 26.3$ MK/s, (b) $q_{\text{eff}} = 136$ kW/cm$^2$, $dT_{\text{liq}}/dt = 176$ MK/s is shown in figure 2 (a, b) respectively. The dimensionless reflected optical signal was defined as measured value divided on reflected optical signal at the beginning of liquid heating. Here, thin and bold lines show the time dependence of the normalized current on the heater resistor and the normalized intensity of the reflected light beam, respectively, the main stages of the explosive phase

![Figure 1. Experimental setup (a), photo of the microheater with size 100x110 µm (b), the morphology of the heater surface (c).](image)

![Figure 2. The dimensionless reflected optical signal depending on the time for explosive vaporization of water: (a) $q_{\text{eff}}=37.6$ kW/cm$^2$, (b) $q_{\text{eff}}=136$ kW/cm$^2$.](image)
change are indicated by letters. Zero time in figure 2 shows the beginning of the current pulse. Stage A-B corresponds to liquid heating, stage B-C corresponds to the time of explosive vaporization, when the microbubbles are appeared and grow up. Stage C-D corresponds to the combining microbubbles into the vapor cavity, the cavity grows and collapse. After cavity collapses, 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 start $t_{init}$.

The variation of the dimensionless reflected optical signal in the time during explosive vaporization of water containing nanoparticles of Aerosil 200 with the volume content of 0.001 is shown in figure 3. For presented data, the effective heat flux $q_{eff}$ and the temperature growth rate $dT_{liq}/dt$ correspond to: (a) $q_{eff} = 32.7$ kW/cm$^2$, $dT_{liq}/dt = 20.2$ MK/s, (b) $q_{eff} = 130$ kW/cm$^2$, $dT_{liq}/dt = 156$ MK/s. Comparing the reflected optical signal depending on the time during explosive vaporization of pure water and water with Aerosil 200 one can see that the nanoparticles lead to the decrease in the time of nucleation and increase the flux of nuclei (decrease the time of vaporization). The existence of the threshold for explosive phase change is seen from the increase in the duration of stage B-C in figure 3 (a).

**Figure 3.** The dimensionless reflected optical signal depending on time for explosive vaporization of water with Aerosil 200 nanoparticles with volume content of 0.001: (a) $q_{eff} = 32.7$ kW/cm$^2$, (b) $q_{eff} = 130$ kW/cm$^2$.

Using the results of numerical calculations of the thermal problem for a multilayer heater and measurements of the time of the nucleation, the dependences of the temperature corresponding to the appearance of vapor bubbles on the rate of liquid temperature growth were determined for pure water and water with silicon oxide nanoparticles. The dependence of the nucleation temperature on the temperature increase rate is shown in figure 4 for pure water and water with Aerosil 200 at particle content of 0.001. The line shows the temperature of superheat limit for water, determined by the equation

$$T_{lim}/T_{cr} = 0.905 + 0.095 (T_{sat}/T_{cr})^8$$

(1)

that obtained from experimental data [7]. It is known that for water, at relatively low rates of temperature growth, the explosive vaporization occurs at the temperature lower than that given by equation (1) due to decrease in the work of nucleation near the metal surface. As can be seen from figure 4, this is also observed for silicon carbide surfaces, which is characterized by the presence of areas with low surface energy and degraded wetting for water. With the increase in the rate of liquid
temperature growth, the temperature of the nucleation for pure water increases and reaches the value of the temperature of the superheat limit given by equation (1). The data for water with silicon nanoparticles shown in figure 4 reveal a decrease in the temperature of nucleation due to the reduction of the work of nucleation in the presence of nanoparticles. This result is important for the development of the methods to control the temperature of explosive vaporization in metastable systems.

4. Conclusions
Results of the present study were obtained using the original optical technique, which allows resolving processes at times of the order of ten nanoseconds during rapid phase change near the microheater surface. It allowed us to find new patterns of the explosive vaporization of the nanofluid formed by water and SiO$_2$ nanoparticles and show that the explosive vaporization in the liquid containing inhomogeneities at the nanoscale occurs in the region of temperatures between the binodal and the spinodal by the mechanism of heterogeneous nucleation. This statement is confirmed by a decrease in the temperature of vaporization and increase in the flux of bubbles stimulated by the nanoparticles.

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