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SPECIFIC FEATURES OF EXPLOSIVE BOILING OF LIQUIDS ON A FILM MICROHEATER

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Explosive boiling of liquids on film heaters under the action of pulsed heat fluxes $q = 10^8$–10^9 W/m^2 *is considered. A technique of stroboscopic visualization of boiling stages with a time resolution of* 100 nsec *is used. Numerous scenarios of evolution of explosive boiling are demonstrated. Conditions of the thermal effect (magnitude of the heat flux, duration and repetition frequency of heat pulses) are found, which ensure single and repeated boiling, intermittent boiling, and boiling with formation of complicated multi-bubble structures. It is noted that homogeneous nucleation is a dominating mechanism of incipience of examined liquids for* $q > 10^8$ W/m^2.

Key words: *explosive boiling, film heater, homogeneous nucleation, boiling regimes.*

Introduction. The interest in explosive boiling of liquids on low-inertia heaters under conditions of high heat fluxes is caused by the use of this process in micromechanical systems [1–3].

Most authors dealing with explosive vaporization considered the mechanism of boiling incipience under pulsed heating. Conditions of vapor-bubble nucleation were studied in [4–7]. It was shown [4, 8] that the contribution of homogeneous nucleation in a superheated liquid becomes rather significant at high growth rates of temperature (greater than 10^6 K/sec) in addition to formation of bubbles on pre-existing boiling centers. A series of experiments on film heaters and ultrathin wires at high growth rates of temperature of the liquid (up to 10^8 K/sec) demonstrated that experimental data agree with predictions of the theory of homogeneous nucleation [4, 8–11]. The results of [10, 11] also indicate that the magnitude of the heat flux affects not only the rate of bubble generation but also the character of the subsequent evolution of vapor structures formed. Repeated boiling and formation of long-living bubbles were noted in those papers.

The present paper describes an experimental study of specific features of explosive boiling of liquids on film microheaters under the action of pulsed heat fluxes $q = 10^8$–10^9 W/m^2. The evolution of explosive boiling under different conditions of the thermal effect (magnitude of the heat flux, duration and repetition frequency of heat pulses) was studied in the experiments.

1. Experimental Setup and Test Techniques. The experiments were performed on a setup schematically illustrated in Fig. 1. Explosive boiling of liquids was initiated by a flat heater, which was the film structure of a cartridge for a jet printer described in [11]. The heater proper was a thin-film resistor 100×100 μm located on a substrate made of glass and covered by a thin layer of silicon dioxide. On the top surface, the resistor was protected by a thin corrosion-proof layer. The heater was placed into a cavity with transparent walls, which was filled by the liquid to be tested. The film resistor was heated by transmitting current pulses from a driver generator (pulse generator G5-56). Based on the measured amplitude of current pulses and the area and electric resistance of the film heater, we determined the instantaneous power released on the heater and the effective heat flux q. The range

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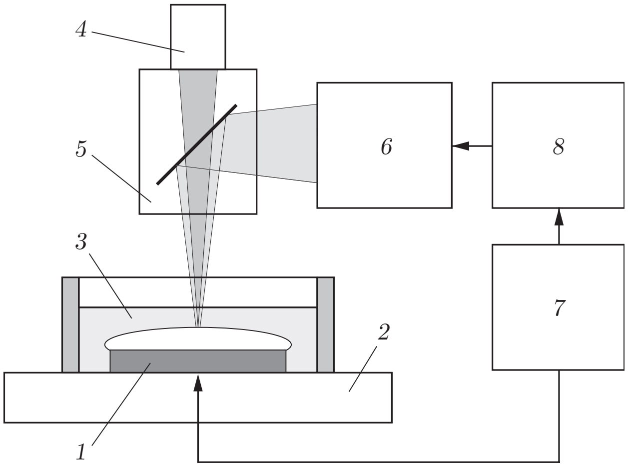

Fig. 1. Setup for visualizing the stages of liquid incipience on a film heater: 1) film microheater; 2) heater substrate; 3) transparent cavity with the liquid; 4) video camera; 5) microscope fitting; 6) stroboscopic system; 7) pulse generator; 8) time-delay system.

of heat-flux values was 10^8–10^9 W/m^2 for a repetition frequency of heat pulses $f = 10$–100 Hz with a duration $\tau_h = 2$–10 μsec.

Explosive boiling of liquids was visualized by the flash videography technique and subsequent reconstruction of stages of fast repeated processes (see, e.g., [12]). In each event of boiling initiated by the action of current pulses, we registered one stage of the process whose beginning was determined by a prescribed delay time from the beginning of heating to the moment of a short-time flash of the stroboscope. For this purpose, the signal from the generator through a time-delay system (pulse generator Hewlett Packard 8112A) was fed to initiate the stroboscopic system (Fig. 1). The minimum delay time was 100 nsec. A light pulse with a duration of 100 nsec was formed by an ISSh-100 stroboscopic lamp. Fresnel lenses were used to increase the intensity and uniformity of illumination of the region where the data were recorded. The process was visualized by a video camera (Toshiba IK-M50H, control unit IK-CU50) with a microscope objective (Mitutoyo M Plan Apo 10) and an optical zoom system (Navitar Zoom ×4), which provided the maximum magnification of ×40 on the matrix (IT-CCD, 752×582 pixels). The technique proposed allowed filming of the stages of the process in two directions: perpendicular to the heater plane (top view) and parallel to the heater plane (side view). The identified stages were recorded, and their sequence was reconstructed. The characteristic time scales of the processes and the geometric sizes of the vapor structures were estimated.

The experiments were performed with liquids (water, toluene, ethanol, and isopropyl alcohol) with significantly different thermophysical properties (surface tension, boiling point, specific heat of vaporization, pressure of saturated vapors, thermal conductivity, and specific heat) [13, 14].

2. Experiment. The results of experiments with variations of conditions of the thermal effect (magnitude and duration of heat pulses) showed that the changes in the character of boiling of liquids on a film heater follow a certain pattern, which can be conventionally presented as a sequence of different boiling regimes. The following boiling regimes are observed for a fixed heat flux q with increasing duration of heat pulses τ_h:

— Boiling regime with generation of single bubbles whose growth does not lead to formation of a continuous vapor cavity covering the heater surface;

— Boiling regime where microbubbles are first generated, then their number drastically decreases, then it increases again, and a vapor cavity is formed (Fig. 2a);

— Boiling regime characterized by generation of a large number of bubbles rapidly forming a vapor cavity with subsequent growth and collapse of the latter (Fig. 2b);

— Regime with repeated boiling after cavity growth and collapse (Fig. 2c), the number of boiling cycles increasing with increasing duration of heat pulses (this effect was also noted in [10, 11]).

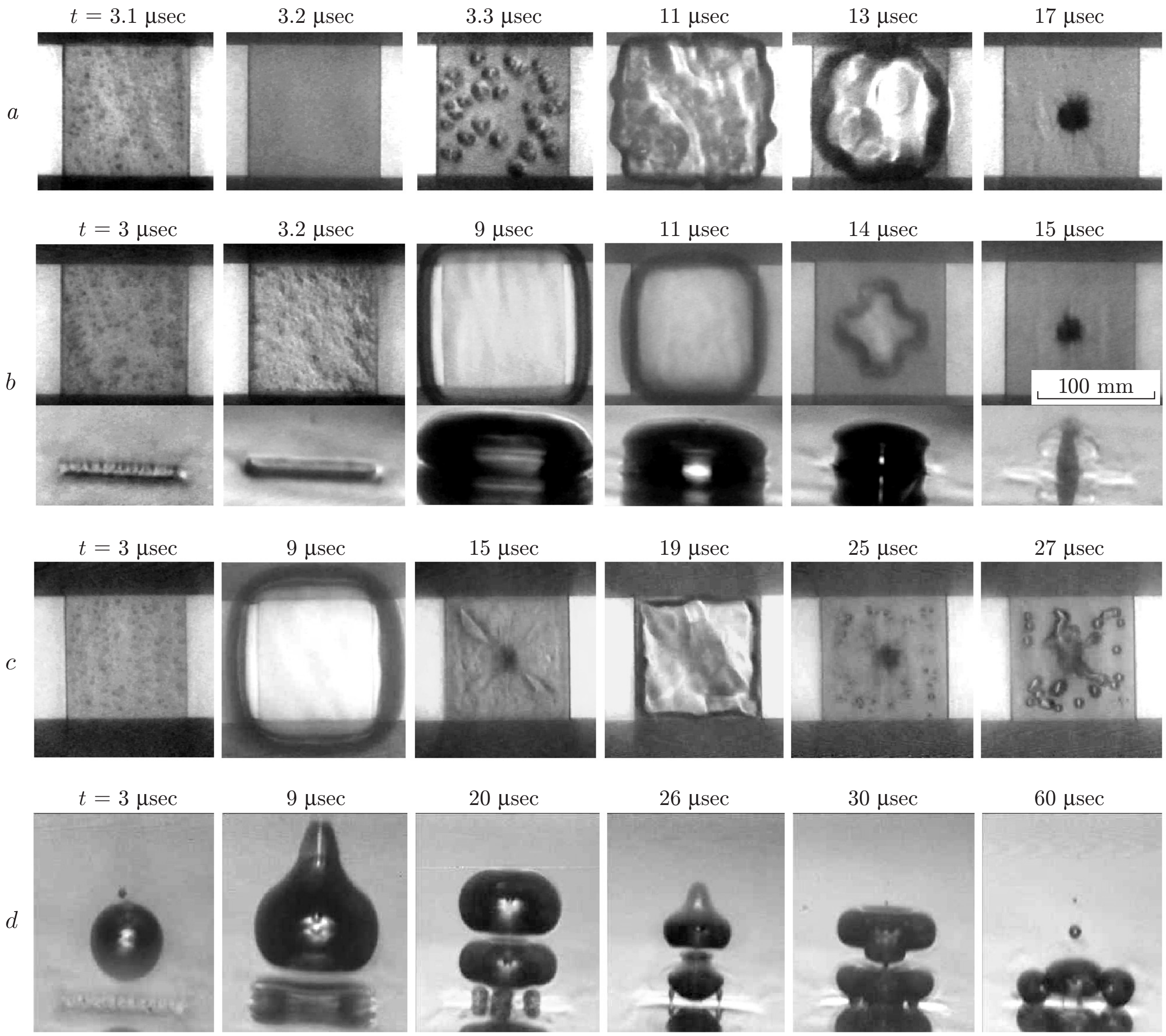

Fig. 2. Regimes of boiling of isopropyl alcohol on a film heater ($q = 4.3 \cdot 10^8$ W/m^2): (a) $\tau_h = 2.6$ μsec and $f = 20$ Hz (top view); (b) $\tau_h = 3$ μsec and $f = 20$ Hz (top view and side view); (c) $\tau_h = 9$ μsec and $f = 20$ Hz (top view); (d) $\tau_h = 3$ μsec and $f = 100$ Hz (side view).

A regular feature in this sequence of boiling regimes is a constant time of boiling incipience t_b after a certain duration of heat pulses. The heat flux q and the corresponding times t_b at which boiling started were found for all liquids under study (Fig. 3). If the action of the heat pulse τ_h was terminated at the moment of boiling incipience t_b, then the subsequent process of boiling included a single act of generation of a large number of bubbles, formation of a vapor cavity, and growth and collapse of the latter. The resultant sets of the values of q and $\tau_h = t_b$ (Fig. 3) corresponded to conditions of the regime of single boiling (see Fig. 2b). This allows us to generalize the laws of the boiling character. For durations of heat pulses greater than the duration of heat pulses corresponding to conditions of single boiling ($\tau_h > t_b$), the boiling process gradually becomes repeating (see Fig. 2c). As the duration of heat pulses becomes smaller [$\tau_h = (0.8\text{–}0.9)t_b$] than the duration of heat pulses corresponding to conditions of single boiling, the regime of intermittent boiling is observed, which is characterized by changes in the number of generated microbubbles (see Fig. 2a). As compared with single boiling, the duration of the process of cavity formation and its subsequence evolution is greater, and the size of the cavity formed is smaller. This difference increases with decreasing duration of heat pulses. Finally, for heat-pulse durations $\tau_h \ll t_b$, no boiling occurs.

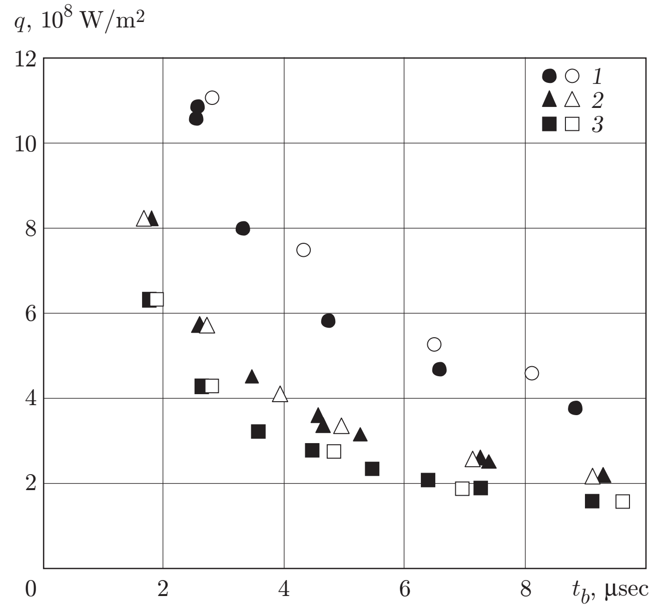

Fig. 3. Boiling incipience in the liquid t_b versus the heat flux q: the filled and open points refer to the experimental data and results of numerical calculations, respectively, for water (1), toluene (2), and isopropyl alcohol (3).

It should be noted that this law of variation of the character of liquid boiling is also observed in the case of variation of the heat flux with a fixed duration of heat pulses.

It was also noted in experiments that the vapor structure formed did not completely disappear after the cavity collapse. For low pulse-repetition frequencies (20 Hz), upward flows of the liquid containing bubbles were formed near the heater surface (see Fig. 2b). The possibility of visualizing heat fluxes under illumination was provided by the difference in density and, hence, optical properties of heated and cold layers of the liquid. As the pulse-repetition frequency was increased (from 20 to 100 Hz), the upfloating bubbles did not disappear but formed a large long-living bubble approximately 100 μm in size (see Fig. 2d). The bubble was formed near the heater surface approximately during 10 sec from the moment the heat pulses were supplied. When the heat pulses were terminated, the bubble disappeared during a period greater than 1 min. If a degassed liquid was used, the bubble was formed in the case of the liquid–atmosphere contact during 3 to 5 min.

The presence of such a bubble exerted a significant effect on the boiling process. A complicated bubble structure was formed; one example of evolution of this structure is shown in Fig. 2d.

3. Discussion. For determining the conditions of explosive boiling of liquids on film heaters, we calculated the changes in temperature of the liquid near the heater $T(t)$ in the course of heating. Modeling of heating of the film structure of the heater and the liquid was based on the numerical solution of two-dimensional heat-conduction equations, which have the following form in the approximation of axial symmetry:

$$\frac{\partial\,(r\rho_i c_i T_i)}{\partial t} = \frac{\partial}{\partial r}\left(r\lambda_i\,\frac{\partial T_i}{\partial r}\right) + \frac{\partial}{\partial z}\left(r\lambda_i\,\frac{\partial T_i}{\partial z}\right) + rq_V(t). \tag{1}$$

Here r and z are the cylindrical coordinates, λ_i, c_i, and ρ_i are the thermal conductivity, specific heat, and density of the medium, the subscript i indicates the number of the layer in the heater–liquid system ($i = 1$ for the liquid, $i = 2$ for the corrosion-proof layer, $i = 3$ for the resistor, $i = 4$ for the silicon-oxide layer, and $i = 5$ for the substrate), and q_V is the specific power of the heat source in the resistor layer.

Equations (1) were closed by the initial conditions $T_i\Big|_{t=0} = T_0$ and by the conditions of heat transfer between the layers, i.e., equality of heat fluxes and temperatures. The condition of zero heat fluxes was imposed on the outer boundaries, because the thermal "disturbances" do not have enough time to reach the outer boundaries during the heat-pulse action.

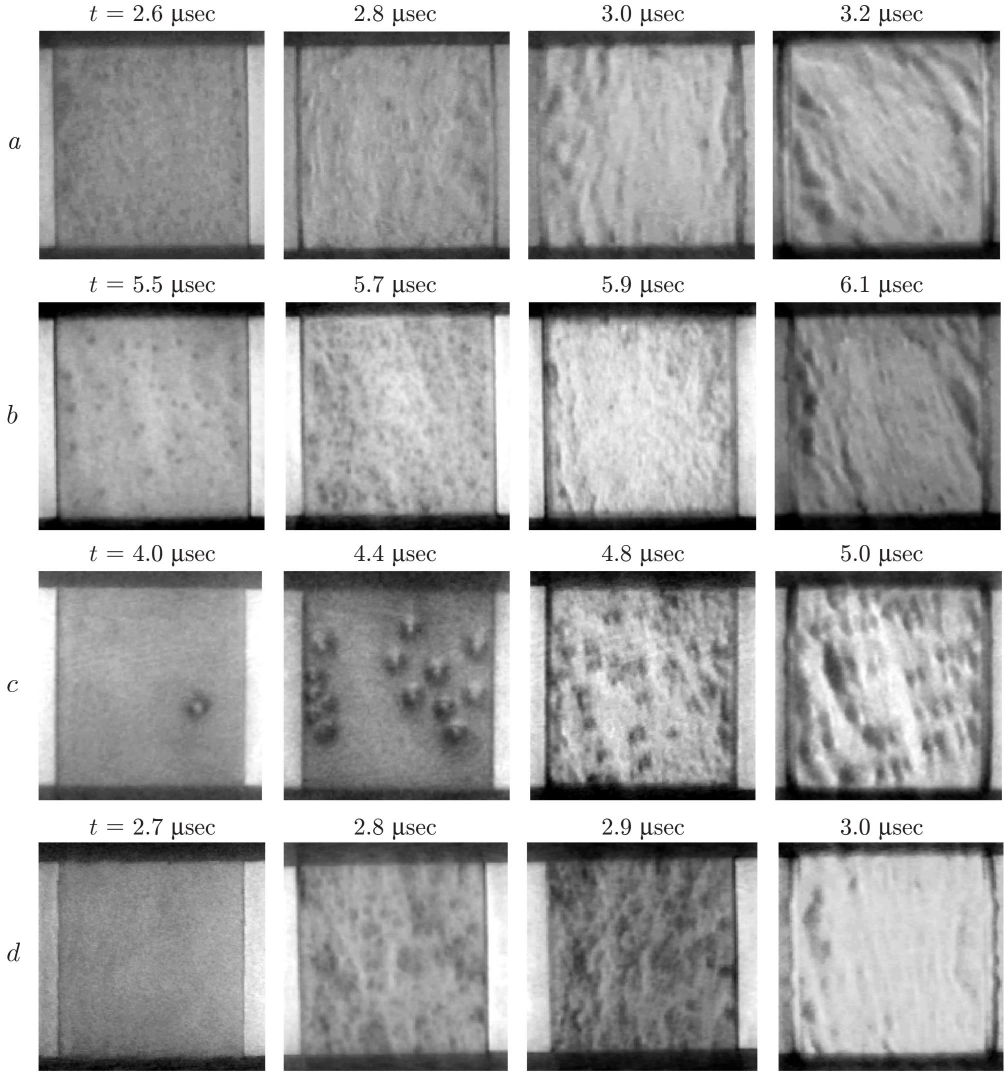

Fig. 4. Initial stage of liquid boiling for isopropyl alcohol (a and b) and water (c and d): (a) $q = 4.3{\cdot}10^8$ W/m^2 and $\tau_h = 2.6$ μsec; (b) $q = 2.4{\cdot}10^8$ W/m^2 and $\tau_h = 5.5$ μsec; (c) $q = 7{\cdot}10^8$ W/m^2 and $\tau_h = 4.8$ μsec; (d) $q = 9.2 \cdot 10^8$ W/m^2 and $\tau_h = 2.8$ μsec.

The boiling incipience was assumed to occur at the time $t = t_b$ when the temperature of the liquid near the heater reached $T = T_b$ at which one bubble was formed on the heater surface of area S. This condition is written as

$$S \int\limits_{t=0}^{t=t_b} J(T(t))\,dt = 1, \tag{2}$$

where $T(t)$ is the temperature of the liquid near the heater surface and J is the rate of nucleation (number of nuclei formed per unit time on a unit surface of the heater). The temperature of the liquid at each time t was determined by solving Eqs. (1). For determining the nucleation rate, it is necessary to identify the boiling mechanism dominating under the examined conditions of the thermal effect.

The test results showed that a large number of bubbles, which are visible through a microscope as point structures, appeared at the time t_b in the examined organic liquids affected by high heat fluxes (see Fig. 4a). After that, a continuous vapor film was formed during 100–200 nsec. As the heat flux was decreased (Fig. 4b), the duration of the process from the moment of origination of microbubbles to their coalescence increased, which made it possible to estimate the density of the generated bubbles as $n > 10^{10}$ m^{-2}. The bubbles were generated at random locations.

In contrast to organic liquids, the first bubbles in water under low heat fluxes (Fig. 4c) appeared on pre-existing centers of vaporization. The number of pre-existing sites on the surface of the heaters used was estimated as $n = 10^8$–10^9 m^{-2}. After that, however, a drastic increase in the number of bubbles was observed. The estimation of the number of bubbles before their coalescence into a vapor film showed that the density of the bubbles was $n > 10^{10}$ m^{-2}. As the heat flux was increased (Fig. 4d), the duration of the process from the moment of origination of microbubbles to the moment of their coalescence into the vapor film became smaller. During the rapid growth of bubbles, their origination on pre-existing centers of vaporization could not be identified. The character of boiling incipience of water became similar to boiling of organic liquids.

Figure 3 shows the times of boiling incipience of the liquids versus the heat-flux density. The dependences are seen to be similar for the examined liquids. Hence, the boiling mechanism for the examined liquids may also be assumed to be similar.

The above-mentioned features agree with the results of [4, 6, 8–11], where a conclusion was drawn that the dominating mechanism of boiling under the action of high heat fluxes is homogeneous nucleation. In accordance with the homogeneous nucleation theory [7, 15, 16], therefore, we can determine the nucleation rate in Eq. (2) with the use of the expression

$$J(T) = \frac{(N_{\rm A})^{2/3}\rho_l(T)\Psi}{\mu}\Big(\frac{6\sigma N_{\rm A}}{\pi\mu(2+P/P_S(T))\omega}\Big)^{1/2}\exp\Big(-\frac{L(T)\mu}{RT}\Big)$$
$$\times\exp\Big(-\frac{16\pi\sigma^3(T)N_{\rm A}\omega}{3RT(P_S(T)-P)^2(1-\rho_v(T)/\rho_l(T))^2}\Big), \qquad (3)$$

where R is the universal gas constant, P is the external pressure, μ is the molecular weight, σ is the surface tension, ρ_l and ρ_v are the densities of the liquid and vapor, respectively, L is the latent heat of vaporization, $N_{\rm A}$ is the Avogadro number, $P_S(T)$ is the pressure of saturated vapor, $\psi = (1+\cos\alpha)/2$ and $\omega = (1+\cos\alpha)^2(2-\cos\alpha)/4$, where α is the contact angle of wetting. The contact angle of wetting in the calculations under the assumption of high wettability of the heater surface was taken to be zero ($\alpha = 0$).

The numerical solution of the heat-conduction equations (1) is based on the use of a second-order implicit conservative scheme, where the condition of heat balance is satisfied exactly. The system of linear equations obtained by approximation was solved by a sweep method. Numerical integration of Eq. (2) was performed by a method of trapezoids. The joint solution of Eqs. (1)–(3) yielded the following values of temperature of the limiting superheating of the liquids: $T_b \approx 587$ K for water, $T_b \approx 539$ K for toluene, $T_b \approx 478$ K for ethanol, and $T_b \approx 465$ K for isopropyl alcohol. These data agree with the results of [4, 9]. The calculated and experimental values of the heat fluxes and the time of boiling incipience are plotted in Fig. 3. It is seen that the difference in the calculated and experimental data for organic liquids is less than 10%. For water, the theoretical predictions were 20% higher than the test results. Such a feature was also noted in [4, 9].

The dependences of the boiling incipience time on the heat flux for all examined liquids (see Fig. 3) also characterize the thermal effect conditions (magnitude of the heat flux q and duration of heat pulses, which were terminated at the moment of boiling incipience $\tau_h = t_b$), which ensure single incipience. These dependences can be conventionally considered as boundaries separating the regions with thermal effect conditions at which explosive boiling occurs or does not occur. It follows from numerical calculations that the temperature of the liquid continues to increase and boiling occurs (see Fig. 2a) if the heat-pulse duration is smaller [$\tau_h = (0.8$–$0.9)t_b$] than the pulse duration corresponding to conditions of single boiling, owing to the thermal inertia of the heater. In contrast to the process of single boiling, the number of generated bubbles first rapidly decreases and then increases again. Apparently, the liquid heating rate reached under these conditions is insufficient to ensure the balance between the amount of heat added to the liquid and the amount of heat necessary for supporting the growth of microbubbles and boiling enhancement. The initially formed microbubbles disappear. A further inertial growth of temperature of the heater surface and the distribution of temperature in the liquid after disappearance of microbubbles again generate conditions for boiling incipience. The intensity of this process, however, decreases. As a result, the process of cavity formation and evolution becomes longer, and the cavity size becomes smaller. Therefore, the observed regime of intermittent boiling may be considered as a transitional regime to single boiling. With a further decrease in the heat-pulse duration, the number of generated bubbles decreases. They do not form a vapor cavity covering the heater surface any longer. No explosive boiling occurs.

If the heat-pulse duration or the heat-flux magnitude is greater than the values corresponding to conditions of single boiling, the heater is further heated. The liquid is separated from the heater by a growing cavity. Because of the low thermal conductivity of vapor, the heat flux from the heater toward the vapor is insignificant. As was shown by calculations, for a heat-pulse duration $\tau_h = 2t_b$, the heater temperature at the time $t = \tau_h$ is almost twice the temperature of boiling incipience. The cavity collapse leads to rapid heating and repeated boiling of the liquid due to the liquid–heater contact (see Fig. 2c). A transition from the regime of single boiling to the regime of repeated boiling occurs.

As was noted in Sec. 2, a complete collapse of the vapor cavity did not occur (see Fig. 2b), and a large bubble was formed near the heater surface if the repetition frequency of heat pulses was increased to 100 Hz (see Fig. 2d). With allowance for conditions of formation of this bubble and its lifetime (see Sec. 2), we can conclude that the effect observed is caused by the presence of the gas dissolved in the liquid.

The assumption on the presence of gas molecules dissolved in the liquid in the vapor cavity offers an explanation for the absence of a complete collapse of the cavity and formation of bubbles near the heater surface. As the repetition frequency of heat pulses increases, the temperature of the liquid layers adjacent to the heater gradually increases under the action of convective flows. The lifetime of the gas bubbles also increases, which favors their coalescence and formation of a large bubble. This assumption agrees with the features observed in the experiments: a long-living gas structure is formed in a multiply repeated process rather than under the action of a single pulse. During the cavity growth and subsequent collapse, the gas bubble is deformed and then destroyed under the action of the arising pressure and due to liquid motion. Complex-shaped bubble structures evolving with time are formed thereby (see Fig. 2d).

Conclusions. Thus, the experiments performed under different conditions of the thermal action reveal the regular features in the sequence of changes in the character of liquid boiling on a film heater under the action of pulsed heat fluxes.

The boiling incipience times versus the heat-flux values are found, which, in turn, determine the conditions of the single explosive boiling regime. As the heat-flux magnitude or heat-pulse duration become smaller than the values corresponding to conditions of single boiling, the boiling process becomes intermittent, which is manifested in drastic changes in the number of bubbles being generated. For heat fluxes and heat-pulse durations greater than the values corresponding to conditions of single boiling, the process of liquid boiling becomes multiply repeated. For repetition frequencies of heat pulses greater than 20 Hz, formation of complicated bubble structures is observed, which results from interaction of the vapor cavity and the gas bubble formed near the heater surface.

The experimental data and their comparisons with theoretical predictions allow us to conclude that homogeneous nucleation is the dominating mechanism of boiling of the examined liquids under the action of heat fluxes $q > 10^8$ W/m^2.

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