EXPLOSIVE BOILING UP OF LARGE WATER DROPS IRRADIATED BY AN INTENSE LASER BEAM

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This paper presents some results of numerical calculations of explosive boiling up of a water drop irradiated by an intense CO_2–laser radiation. The theoretical model of the drop explosion has been constructed based on simultaneous solution to the boundary–value problem on thermal diffusivity through an inhomogeneousity heated drop and of the kinetic equation of vaporization of a superheated (metastable) liquid. The basic characteristics of explosive boiling up of the drop (degree of explosive vaporization, time of explosion, its energy threshold) have been investigated. It has been established that these characteristics depend on the heating rate of the drop and its radius. The results presented in this paper are indicative of the fact that two drop heating regimes can be identified in the process of explosive boiling up of large drops from the point of view of its evolution, namely, slow and fast heating regimes. This division indicates the competition among real physical processes in the irradiated drop and makes it possible to identify the salient features of explosion process.

Interaction of intense laser radiation with absorbing liquid particles is the subject of many theoretical and experimental investigations.[1-9] It is well known that absorbing drops irradiated by a laser beam evaporate and under certain conditions, for example, when the rates of their heating exceed threshold values, evaporation becomes explosive in nature (see, Refs. 1, 2, and 10). As this takes place, the particle comes to the boil practically instantaneously (in comparison with total time of its heating up by the time of explosion), because a liquid inside the particle is highly superheated,[2] and vapour bubbles being formed cause fragmentation of the drop with the formation of a biphase mixture of vapour and particle fragments. Such a regime of vaporization is named phase explosion[1-2] or explosion–fragmentation.[1] It should be noted that another regime of explosion named super–critical can be realized when rates of heating up of the absorbing particles are higher than 10^{11} K/s. In this case superheated liquid changes to gas by passing the critical point.

Previous investigations[4] into the explosion of homogeneously absorbing drops (for $\alpha_{ab}\, a_0 \ll 1$, where α_{ab} is the absorptance of a liquid and a_0 is the initial drop radius) showed that postexplosive evolution of the region of radiation interaction with the aerosol (and, above all, the optical characteristics of this region) is determined to a large extent by such parameters of explosive boiling up of drops as the degree of explosive vaporization, time of explosion, and disperse composition of fragments. Strong dependence of these parameters first of all, on the heating rate of particle was established. However, the question about the form of this dependence for large particles is still an open question. Our investigations presented below tackle this problem.

It was shown in Ref.4 that one of the basic integral characteristics of explosion is the degree of explosive vaporization of a drop X_{ex} defined as

$$X_{ex} = M_v/M_0 ,$$

where M_v, is the mass of vapour produced in the process of explosion of the drop with the initial mass M_0.

The vapour phase inside a particle is caused by the formation of vapour bubbles and their subsequent growth in metastable liquid. Thus

$$X_{ex} = \frac{1}{M_0} \int_0^{t_{ex}} dt' \int_{V_L} J\,[T(\mathbf{r})]\, m_v(t_{ex} - t')\, dV , \qquad (1)$$

where J is the rate of homogeneous nucleation,[11] m_v is the vapour mass in a growing bubble that was formed at the time t', V_L is the volume of metastable liquid, and t_{ex} is the time of explosive boiling up of the drop.

Let us determine the time of explosive boiling up of the drop t_{ex} as the time interval from the start of heating to the instant of explosive vaporization X_{ex}. Thus, explosion time is a sum of the time of heating of a drop to the temperature of explosive boiling up and the time of formation of vapour phase by the time of drop fragmentation.

Thermodynamic threshold of explosive vaporization X_{ex}^t is

$$X_{ex}^t = \frac{1}{Q_e M_0} \int_{V_L} \rho_L\, C_p [T(\mathbf{r},\, t_{ex}) - T_B]\, dV , \qquad (2)$$

where Q_e is the vaporization heat of liquid, T_B is the temperature of normal boiling point, θ_L and C_p are the density and isobaric heat capacity of liquid. Relation (2)

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means that the whole heat stored in metastable regions inside the drop is consumed solely for changing liquid into vapour bubbles. It follows from Eq. (2) that $X^{t}_{ex} \cong 0.41$ for the Π–shaped profile of a temperature inside the particle. The temperature of explosion is, as a rule, in the interval $T_{ex} \cong 578–593$ K at normal atmospheric pressure, with $T_{ex} \cong 578$ K corresponding to the case of boiling up of a liquid in a relatively large volume and $T_{ex} \cong 593$ K being the temperature of spinode at which a catastrophic increase in the number of the vapour centers is observed. The relative part of liquid changing into the metastable state is determined, above all, by the rate of light energy pumping into the drop and by the volume of the region of energy release depending on the drop size. The parameters of explosion (rate of separation of superheated layers and phase and disperse composition of explosive products) are functions of the degree of superheating of liquid.

It was shown in Refs. 2 and 4 that the condition of explosion of a liquid particle is the fulfilment of the equality

$$\int_0^{t_{ex}} dt' \int_{V_L} J\,[T(\mathbf{r})]\, m_v(t_{ex} - t')\, dV =$$

$$= \frac{1}{Q_e} \int_{V_L} \rho_L\, C_p [T(\mathbf{r}, t_{ex}) - T_B]\, dV, \qquad (3)$$

the left side of which represents the mass of vapour M_v accumulated in vapour bubbles by the time of explosion and the right side represents the maximum possible value of this mass produced due to explosive vaporization of a superheated liquid. Relation (3) determines the time of explosion t_{ex} and the degree of explosive vaporization $X_{ex} = M_v(t_{ex}) / M_0$.

The vapour mass m_v in a vapour bubble of radius a_d can be determined as

$$m_v(t_{ex} - t') = 4/3\, \pi\, \rho_v \left[\int_{t'}^{t_{ex}} v_v\, dt \right]^3,$$

where ρ_v is the vapour density. The rate of bubble growth v_v depends on the temperature of liquid in the vicinity of bubble. The initial values of v_v are in the range ~ 40–20 m/s. The Rayleigh model gives $v_v \cong 100$ m/s. In this paper we did not solve the general problem on the bubble growth in a superheated liquid (see, for example, Ref. 12), but restricted ourselves to the models with $v_v = \text{const}$.[4]

The parameters listed below are of primary importance for investigation into the dynamics of explosion. They are:
– local degree of vaporization of superheated regions inside a drop,

$$X_{loc} = M_v(t_{ex}) / M_m(t_{ex}),$$

where $M_m = \int_{V_L(T>T_B)} \rho_L dV$ is the mass of metastable liquid in a drop,

– total number of vapour bubbles formed by the time of explosion

$$N_v = \int_{V_L(T>T_B)} dV \int_0^{t_{ex}} J\, dt$$

– average size of a bubble $\bar{a}_d$, that gives us knowledge of the size distribution of the condensed phase of explosive products.[4]

We restrict ourselves to the consideration of only isobaric heating regimes. This means that boiling–up regions of scale L must depressurize in time being much smaller than the time of explosion of a drop, that is, $t_{ex} \gg t_s = L / c_s$, where c_s is the sound velocity in a liquid. This condition imposes a limitation on the maximum heating rate J_h. Estimates show that the drop heating can be considered to be isobaric at $J_h \le 10^{10}$ K/s. It is obvious that anisobaric heating should result in a delayed explosion, because the frequency of homogeneous nucleation and the rate of growth of vapor bubbles decrease as the pressure of a liquid rises.[11]

Mathematical formulation of the problem on heating of a spherical particle by optical radiation includes the equation of the heat diffusivity through a drop in spherical coordinate system with corresponding initial and boundary conditions.[9]

$$\frac{dT}{dt} = \frac{1}{r^2}\frac{d}{dr}\left(a_L\, r^2 \frac{dT}{dr} \right) + \frac{1}{r^2 \sin\theta}\frac{d}{d\theta}\left(a_L \sin\theta \frac{dT}{d\theta} \right) +$$

$$+ Q(r, \theta, R), \qquad (4)$$

where $0 < r < R(\theta, t)$; $0 < \theta < \pi$, and $t > 0$

On the drop surface ($r = R(\theta, t)$) we have

$$\lambda_L \left(\frac{dT}{dr} - \frac{1}{r^2}\frac{dR}{d\theta}\frac{dT}{d\theta} \right) \left(1 + \left(\frac{dR}{d\theta} \right)^2 \right)^{-1/2} =$$

$$= \rho_L Q_e(T^*) \left(\frac{dR(\theta, t)}{dt} - \frac{dR(\theta, 0)}{dt} \right),$$

$$\frac{dR(\theta, t)}{dt} = -C \exp\left[-\frac{\rho_L Q_e(T^*)}{n_d\, k_B\, T^*} \right], \; T^* = T(R, \theta, t), \qquad (5)$$

$$|T(0, \theta, t)| < \infty, \quad \left.\frac{dT}{dr}\right|_{r=0} = 0; \quad \left.\frac{dT}{d\theta}\right|_{\theta=0} = \left.\frac{dT}{d\theta}\right|_{\theta=\pi} = 0.$$

Initial conditions have the form

$$T(r, \theta, 0) = T_0, \; R(\theta, 0) = a_0.$$

Here $Q(r, \theta, R) = \frac{4\pi n k\, I\, B}{\lambda\, C_p\, \rho_L}$, $B = \frac{1}{E_0^2}(E_r E_r^* + E_\theta E_\theta^* + E_\phi E_\phi^*)$, $E_i (i = r, \theta, \phi)$, T is the temperature in a point inside the drop, λ_L is the thermal conductivity of the material of the particle, I is the radiant intensity, n_k and k_B are the number of molecules per unit volume and the Bolzmann constant, respectively, and n and k are the real and imaginary parts of the refractive index of a liquid.

On the right side of the boundary condition we omitted the components responsible for the heat exchange between drop surface and ambient gas and for the convective outflow of heat from the particle. This is caused by the fact that heat losses in the considered range of heating rates ($\geq 10^7$ K/s) are much lower than the energetic losses due to vaporization of the drop.[9]

The form of equation for vaporization of the drop (5) corresponds to the gas–kinetic regime,[10] in which we can neglect the counter pressure of air and condensation of vapor molecules on the drop. The value of C, depending on the condensation coefficient was set equal to 10^6 cm/s, as in Ref. 9. A procedure for numerical solution of the boundary–value problem given by Eqs. (4) and (5) was described in detail in Ref. 9. It should be noted that difference scheme used in Ref. 9 becomes unstable for high radiant intensities ($I = 10^7 - 10^8$ W/cm^2) because of large temperature gradient in near–surface region of a drop. To avoid this instability, we replace a reciprocal difference derivative in expression (5) by the central one.

We have performed the numerical solution of Eqs. (3)–(5) for unpolarized radiation of a CO_2–laser with the wavelength $\lambda = 10.6$ μm irradiating water drops with $m = 1.18 - 0.82\,i$ at $T_0 = 283$ K for $\rho_L = 10$ kg/m^3, $C_p = 4{,}18 \cdot 10^3$ J(kg·K), $Q_e = 2496 \cdot 10^6$ J/kg, $\lambda_L = 0.6$ W/(m·K), $n_0 = 1$, and $\nu_\nu = 40$ m/s.

The temperature dependence of heat transfer parameters of a liquid was ignored in calculations because the refined calculations of the explosion characteristics made with allowance for this dependence did not differ by more than 10% (see Ref. 9). This difference, as a rule, is less than experimental errors.

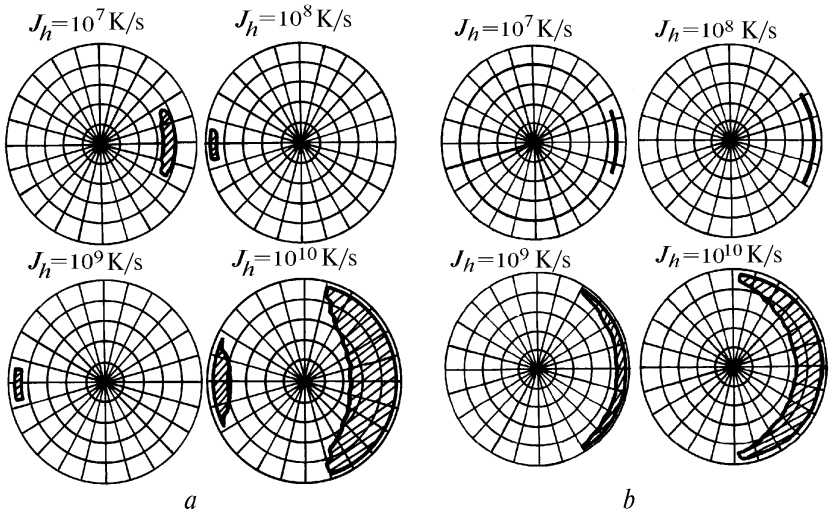

FIG. 1. Configuration of explosive boiling–up zones inside water drops of different initial radii $a_0 = 10$ (a) and 25 μm (b) as a function of the rate of their heating by radiation propagating from right to left.

The condition of boiling up was checked in each time step for each spatial cell of a calculational grid. It corresponds to the average time of formation of a vapor bubble in the volume ΔV being small in comparison with the time of heating of this volume to the temperature T_i in the cell. When this condition was satisfied, the temperature in this cell was fixed that is, it remained constant until termination of calculations [fulfilment of relation (3)]. At each moment we determined the configuration of the vapor zone inside the particle individually in shadowed and illuminated hemispheres of the drop, its volume V_{ex}, vapor mass M_ν, total number of vapor bubbles N_ν, and their average size $\bar{a}_d = M_\nu / N_\nu$.

Now let us analyze the calculated results. Figures 1 *a* and *b* show the configuration of boiling–up zones inside drops of different initial radii (principal sectional view) at different heating rates characterized by the parameter[3]

$$J_h = \frac{\alpha_{ab}\, w_p}{\mathbf{B}_m\, \rho_L\, C_p\, t_p},$$

where w_p is the energy density in the laser pulse of width t_p, B_m is the maximum value of inhomogeneity factor of the internal optical field.[9] For rectangular pulse

$$J_h = \frac{\alpha_{ab}\, I_0}{B_m\, \rho_L\, C_p\, t_p},$$

where I_0 is the radiant intensity.

As is seen from Fig. 1, the general tendency has been to this zone to expand with the increase of the parameter J_h. This is due to the fact that at low heating rates the rate of growth of vapor bubbles formed in the regions of maximum heat release is comparable or higher than the rate of formation of new vapor centres. Thus, only a small region inside the drop vaporizes by the time of explosion. The reverse process is observed at high heating rates, when $J_h > 10^9$ K/s: vapor bubbles are large in number and have no time to increase their volumes markedly, while the boiling–up region expands.

The interesting process is observed in the drop of radius $a_0 = 10$ μm. When J_h increases from 10^7 K/s to 10^{10} K/s, at first the boiling–up zone shifts from the illuminated hemisphere towards the shadowed zone, and then liquid comes to the boil in both shadowed and illuminated hemispheres (see Fig. 1*a*). The spatial distribution of the factor B over the diameter of the drop explains this fact. It is seen that a narrow maximum in B occurs in the shadowed hemisphere near the surface of the drop of $a_0 = 10$ μm (see curves for B in Fig. 2). At

$J_h = 10^7$ K/s the large temperature gradient in this region has enough time to smear as a result of thermal conductivity to cold layers of a liquid (Fig. 2*a*, curve *1*), and the liquid comes to the boil only in the illuminated hemisphere, where the gradient is low. With the increase of the heating rate the temperature profile inside the drop practically duplicates the profile of B (Fig. 2*a*, curve *3*) and for this reason condition (3) is fulfilled in both hemispheres.

Figure 3 shows the degree of explosive vaporization X_{ex} as a function of the heating rate of drops of different radii. It follows from Fig. 3 that the form of the function $X_{ex}(J_h)$ is primarily determined by the character of radiation absorption (homogeneous or inhomogeneous). Really, for homogeneously absorbing particles, whose radii $a_0 < (2\alpha_{ab})^{-1}$, a monotonic increase in the degree of explosive vaporization is observed starting from some value of J_h (corresponding to a threshold heating rate J_h^t) followed by its fast saturation. When the absorption inside a drop is essentially inhomogeneous [$a_0 \approx (2\alpha_{ab})^{-1}$], X_{ex} at first decreases with the increase of J_h, but then also sharply increases approaching the limiting value at the spinode: $X_{ex}^t = 0.41$. A minimum in the function $X_{ex}(J_h)$ at $a_0 = 10$ μm can be explained by the above–pointed shift of boiling–up zone from the illuminated hemisphere of the drop to the shadowed zone with the subsequent decrease of the boiling–up volume V_{ex} (Fig. 4). For $a_0 > (2\alpha_{ab})^{-1}$ a dip in the function $X_{ex}(J_h)$ practically disappears as the radius of the particle increases. Degree of explosive vaporization depends weakly on the heating rate for the most part of the considered interval of variation of the parameter J_h and starts to increase only at $J_h \sim 10^{10}$ K/s. The behavior of local degree of vaporization X_{loc} practically duplicates the function X_{ex} for the homogeneous case (Fig. 3, curve *1*) that is, X_{loc} varies in the range 0.1 – 0.4 as J_h increases from 10^7 to 10^{10} K/s.

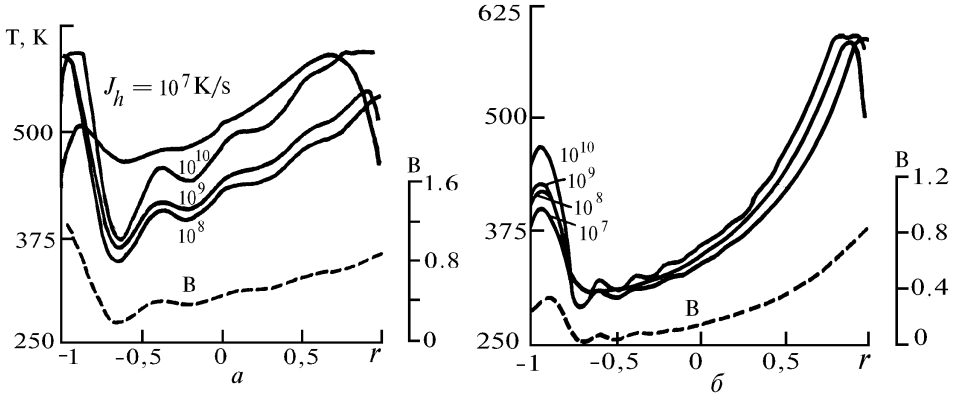

FIG. 2. The temperature profile (principal sectional view) inside drops of $a_0 = 10$ (a) and 25 μm (b) by the time of their explosion at different heating rates. Dashed curve shows the profile of the parameters B.

Numerical studies of the threshold density w_{ex} of the radiant energy required for explosion of a water drop have shown that the parameter w_{ex} depends weakly on both the J_h and the initial size of the particle in the considered range of variation of the thermal pump rates $J_h < 10^{10}$ K/s (Fig. 5). As for explosion time, as is seen from Fig. 6, $t_{ex} \sim 1/J_h$ and it is practically independent of a_0. This demonstrates that the basic parameters characterizing the process of phase explosion of absorbing drops of arbitrary radius (explosion time t_{ex} and threshold energy density w_{ex}) can be quite generally described by corresponding relations for homogeneously absorbing particles

$$t_{ex} \cong \frac{(T_s - T_0)}{J_h}; \quad w_{ex} \cong \frac{\rho_L C_p (T_s - T_0)}{\alpha_{ab}}.$$

The results of calculations show that the rate of the vapor bubble growth ν_v used in the model, influences only the total number of bubbles and their average size and practically has no effect on the other integral characteristics of the process, namely, on the degree of vaporization X_{ex} and the threshold energy density of explosion w_{ex}. The calculations carried out for lower rate of the bubble growth $\nu_v = 20$ m/s have shown that N_v increases nearly twice while X_{ex} and w_{ex} change by no more than 5%.

The results presented here point out that two heating regimes can be identified from the point of view of the evolution of explosive boiling up of large drops, namely, slow and fast heating regime. Although this division is rather conventional, it indicates the competition among real physical processes inside an irradiated drop and makes it possible to identify the salient features of the explosion.

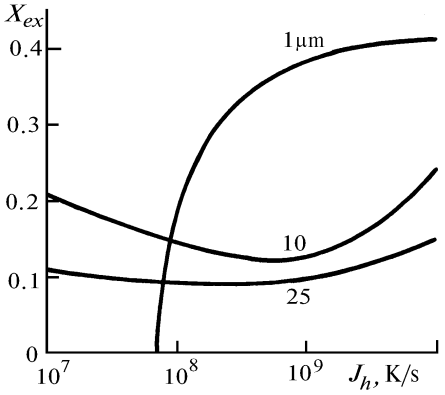

FIG. 3. The degree of explosive vaporization of particles of different radii as a function of the heating rate.

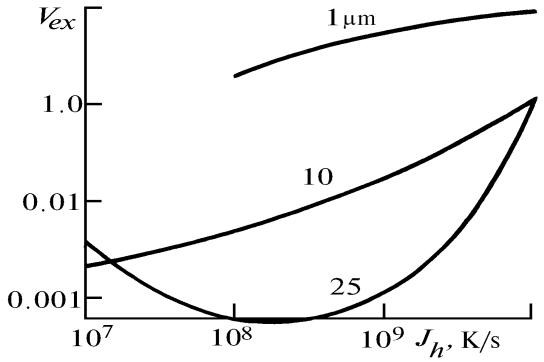

FIG. 4. Normalized volume of boiling–up zones vs the parameter J_h.

In the first regime the heat exchange among the layers of liquid plays a decisive role in the formation of temperature profile inside a drop. As a result, boiling up occurs primarily in the region with low initial temperature gradient, e.g., in the illuminated hemisphere of a particle. Violent nucleation beginning here leads to the drop explosion before the other initially cold regions of the drop come to the boil. This heating regime is characterised by the low degree of explosive vaporization X_{ex} and relatively large times of explosion $t_{ex.}$ In this case the number of bubbles N_v is small (Fig.7).

In fast heating regime the thermal conductivity has no time to smooth noticeably the temperature profile inside a drop, thus, boiling up begins in the regions with maximum value of the factor B contrary to the previous regime. The rate of heating of a liquid by radiation becomes comparable with the vaporization rate in boiling–up zones. That results in envolving of new and new regions of a drop in the nucleation process. In this case the vapor centres N_v grow in number and their average size $\overline{a}_d$ decreases. The high nearly–limiting values of the degree of explosive vaporization X_{ex} and short explosion times t_{ex} are characteristic of this regime.

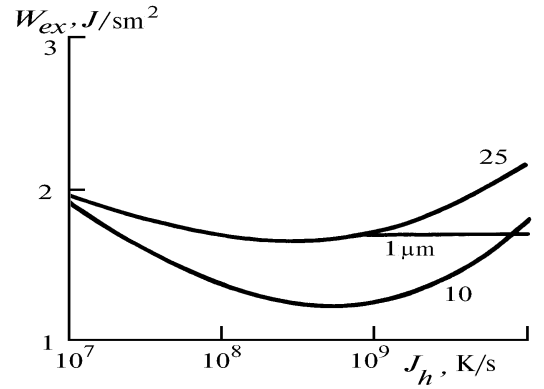

FIG. 5. Density of laser energy required for explosion of the drop vs the heating rate.

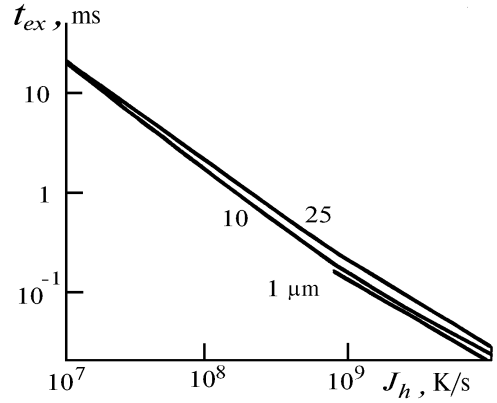

FIG. 6. Explosion time of the drop vs the heating rate.

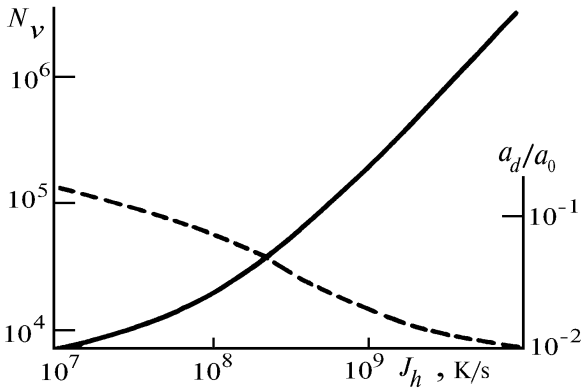

FIG. 7. Total number of vapor bubbles being formed by the time of explosion of the drop of a_0 = 10 μm (solid curve) and average size of vapor bubbles (dashed curve) vs the parameter J_h.

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