HOMOGENEOUS HEATING, EVAPORATION AND EXPLOSION OF A WATER AEROSOL DROP

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Pre-explosion heating of a drop of aqueous aerosol is considered for conditions where thermal conductivity and pressure gradients within the drop may be neglected.

Intense heat liberation into a drop of aqueous aerosol can lead to attainment of the absolute instability temperature of water within the drop, followed by explosive destruction [1]. Depending on the intensity of heat liberation, size of the drop, and other conditions, different variants of explosive destruction can be realized [2]. From the viewpoint of drop hydrodynamics we can distinguish two explosion regimes: in the one, thermal conductivity within the drop is significant [3, 4], while in the other, pressure gradients and liquid motion (convection) within the drop play the major role [5]. We also have an isochoric regime (very rapid, over a time $t_0 < r_0/a$, where r_0 is the initial drop radius and a is the speed of sound in water) with subsequent explosive ejection of liquid [6]. Aside from these three modes, there also exists a regime in which both temperature and pressure gradients within the drop can be neglected. Liquid motion will be produced by thermal expansion. The present study will consider the convective explosive drop heating regime.

For sufficiently small drops (r_0 = 1-10 μm) the approximation of a homogeneous optical field within the drop is valid [4]. With consideration of the dependence of the mean volume index of absorption α (m^{-1}) on the density of water [7] $\alpha = \alpha_0(\rho/\rho_0)^2$ the heat liberation function q(W/m^3) can be written in the following form: $q = \alpha_0(\rho/\rho_0)^2 I_0 I(t)$, where I_0 is the characteristic radiation intensity: ρ_0 is the initial density of the water; α_0 (10^4-10^5 m^{-1} for the infrared range [8]) is the initial radiation absorption coefficient; $I(t)$ is a dimensionless function describing the form of the radiation pulse over time. We take the initial temperature of the surrounding air and drop equal to T_0 = 288.15 K, the initial pressure $p_\infty = 1.01\cdot10^5$ N/m^2, then p_0 = 999.0 kg/m^3, the specific volume $v_0 = 1/\rho_0 = 1.001\cdot10^{-3}$ m^3/kg.

It will be convenient to describe drop heating and evaporation using dimensionless variables. We choose as characteristic quantities: the thermodynamic properties of water at the critical point [9] – density ρ_{cr} = 317.76 kg/m^3, pressure $p_{cr} = 221.15\cdot10^5$ N/m^2, temperature T_{cr} = 647.27 K, enthalpy $h_{cr} = 2.0952\cdot10^6$ J/kg; dynamic viscosity and thermal conductivity coefficients at T = 583 K (explosion temperature in the thermal conductivity regime [4]), $\eta_0 = 8.65\cdot10^{-5}$ kg/(m·sec), λ_0 = 0.522 W/(m·K); ratio h_{cr}/T_{cr} for the specific heat of water C_p; initial radius r_0 = 1-10 μm; heat liberation intensity $q_0 = \alpha_0(\rho_{cr}/\rho_0)^2 I_0$, time $t_0 = \rho_{cr}h_{cr}/q_0$, velocity $u_0 = r_0/t_0$.

The undimensionalized equations of conservation of mass, momentum, and energy for the spherically symmetric case can be written as [10]:

$$\frac{\partial}{\partial t}\rho + \frac{1}{r^2}\frac{\partial}{\partial r}(r^2\rho u) = 0, \tag{1.1}$$

$$\rho\left(\frac{\partial}{\partial t} + u\frac{\partial}{\partial r}\right)u + \mathrm{Eu}\,\frac{\partial\pi}{\partial r} = \frac{4}{3\,\mathrm{Re}}\left\{\eta\,\frac{\partial^2 u}{\partial r^2} + \ldots\right\}, \tag{1.2}$$

$$\frac{\partial}{\partial t}[\rho(\mathrm{E} + A_1u^2/2)] + \frac{1}{r^2}\frac{\partial}{\partial r}\left\{r^2\left[\rho u(h + A_1u^2/2) - \lambda/\mathrm{Pe}\,\frac{\partial\tau}{\partial r} + \frac{4}{3}\frac{A_1}{\mathrm{Re}}\eta\left(\frac{u}{r} - \frac{\partial u}{\partial r}\right)\right]\right\} = I(t)/\varphi^2, \tag{1.3}$$

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$$\mathrm{Eu} = \frac{p_{\mathrm{cr}}}{\rho_{\mathrm{cr}} u_0^2}; \quad \mathrm{Re} = \frac{\rho_{\mathrm{cr}} r_0 u_0}{\eta_0}; \quad \mathrm{Pe} = \frac{\rho_{\mathrm{cr}} h_{\mathrm{cr}} r_0 u_0}{\lambda_0 T_{\mathrm{cr}}};$$

$$A_1 = \frac{u_0^2}{h_{\mathrm{cr}}}; \; h = \mathrm{E} + A_2 \frac{\pi}{\rho}; \; A_2 = \frac{p_{\mathrm{cr}}}{\rho_{\mathrm{cr}} h_{\mathrm{cr}}}.$$

Here t, r, u are dimensionless time, coordinate, and radial velocity component; η, λ are dimensionless dynamic viscosity and thermal conductivity coefficients.

The relative values of pressure, temperature, and specific volume ($=1/\rho$) are denoted by π, τ, φ, as in thermodynamics [11], the specific internal energy and enthalpy by E and h. The Euler number Eu and inverse Reynolds number Re^{-1} define the ratio of the pressure and viscosity forces to inertial forces (velocity head); the Peclet number Pe is the ratio of the convective enthalpy flux to the thermal conductivity heat flux; the dimensionless parameters A_1, A_2 are the ratios of the characteristic specific kinetic $u_0{}^2$ and elastic p_{cr}/ρ_{cr} energies to the characteristic enthalpy of the water h_{cr}.

For the equation of state of water we take Himpan's expression [12], obtained by use of experimental data at the boiling and critical points:

$$\left[\pi + \frac{a}{(\varphi - b)(\tau\varphi - c)}\right](\varphi - d) = s\tau, \tag{2}$$

$$s = \frac{R}{\mu}\frac{\rho_{\mathrm{cr}} T_{\mathrm{cr}}}{p_{\mathrm{cr}}} = 4{,}2923; \; a = 10{,}788; \; b = 0{,}2613; \; c = -1{,}8523; \; d = 0{,}2986.$$

Here $R = 8.314 \cdot 10^3$ J/(kmole·K) is the universal gas constant, $\mu = 18.015$ kg/mol is the molar mass of water. The constants a, b, c, d, s are calculated in accordance with the critical parameters presented in [9]. Equation (2) is significantly more precise than the Van der Waals equation of Kuznetsov's approximation formulas [13] over a wide parameter range, including the critical point. On the other hand, this equation is significantly more simple and more convenient for applications than the international equation of state of water [9].

The conditions Eu = 1, Pe = 1, Re = 1 permit determination of characteristic velocities: $u_p = \sqrt{p_{cr}/\rho_{cr}} = 264$ m/sec, $u_\lambda = \lambda_0 T_{cr}/(\rho_{cr} h_{cr} r_0) = 0.507\text{-}0.0507$ m/sec (for $r_0 =$ 1-10 μm), $u_\eta = \eta_0/(\rho_{cr} r_0) = 0.272\text{-}0.0272$ m/sec $\sim u_\lambda$, which corresponds to characteristic heat liberation intensities: $q_p = \rho_{cr} h_{cr} u_p / r_0 = 1.75 \cdot 10^{17}\text{-}1.75 \cdot 10^{16}$ W/m^3, at which the pressure gradient is comparable to the velocity head, and $q_\lambda = \lambda_0 T_{cr}/r_0{}^2 = 3.38 \cdot 10^{14}\text{-}3.38 \cdot 10^{12}$ W/m^3, for which the thermal conductivity heat flux $-\lambda(\partial T/\partial r)$ is comparable to the convective water enthalpy flux $\rho u h$. Analysis of conservation equations (1) with use of these estimates indicates that from the viewpoint of flow hydrodynamics and heat exchange within the drop the following five heating and explosion regimes can be distinguished:

1) thermal conductivity, $q_0 \ll q_\lambda$, $u_0 \ll u_\lambda$, $t_0 \sim t_\lambda = r_0/u_\lambda$;
2) thermal conductivity-convective, $q_0 \sim q_\lambda$, $u_0 \sim u_\lambda$, $t_0 \sim t_\lambda$;
3) convective, $q_\lambda \ll q_0 \ll q_p$, $u_\lambda \ll u_0 \ll u_p$, $t_p = r_0/u_p \ll t_0 \ll t_\lambda$;
4) nonisobaric, $q_0 \sim q_p$, $u_0 \sim u_p$, $t_0 \sim t_p$;
5) isochoric, $t_0 < t_a = r_0/a$, $q_0 > q_a = \rho_{cr} h_{cr} a / r_0 \approx 10^{18}\text{-}10^{17}$ W/m^3.

In regime 1 we may neglect the viscosity of the water, and linearization of Eq. (1.3) permits complete elimination of the convective term, with only thermal conductivity remaining. In regimes 1-3 the change in pressure with change in coordinate r within the drop can be neglected, while in regimes 3-5 thermal conductivity and viscosity can be neglected. Thus, friction and energy dissipation forces can be neglected for all explosive regimes just as for all evaporation regimes (see, for example, [14]).

We will now turn to the convective regime. With regard to optical radiation intensity the convective regime is realized (at $\alpha_0 = 8 \cdot 10^4$ m^{-1}) in the range: $4.2 \cdot 10^{10}\text{-}4.2 \cdot 10^8$ W/m^2 $\ll I_0 \ll 2.2 \cdot 10^{13}\text{-}2.2 \cdot 10^{12}$ W/m^2. Since Eu $\gg$ 1, the momentum conservation equation (1.2) is $\partial p/\partial r = 0$. Consequently, the pressure within the drop depends only on time and is defined by the pressure $p_d(t)$ on its surface. We find the latter from the equation of conservation of momentum on the drop surface at $r = r_d$: $p_d + \rho_d u_d{}^2$, where p_ℓ, ρ_ℓ, u_ℓ are the pressure, density, and vapor velocity at the outer boundary of the Knudsen layer [15], the thickness of which is significantly less than r_d. Evaporating molecules arrive in this layer because of collisions with the equilibrium Maxwell velocity distribution. Neglecting the velocity head of the water and considering the shifts in pressure $p_\ell = f_p(M_\ell)p_s(T_d)$ and temperature $T_\ell = f_T(M_\ell)T_d$ (where $p_s(T_d)$ is the saturated vapor pressure at the temperature of the drop surface T_d; $M_\ell = u_\ell/\sqrt{\gamma RT_\ell/\mu}$ is the Mach number; $\gamma = 1.333$ is the adiabatic index of the vapor, which we will consider an ideal gas; the functions $f_p(M_\ell)$, $f_1(M_\ell)$ being presented in [15]), we obtain the final expression for the dimensionless pressure

$$\pi_d(T_d) = \pi_\ell(1+\gamma M_\ell^2). \tag{3}$$

We will note that the Mach number M_ℓ and pressure p_ℓ are related by the isoentropic relationship [10, 16] to the vapor pressure at infinity p_∞, where the vapor pressure may be considered zero: $p_\infty/p_\ell = (1+\frac{\gamma-1}{2}M_\ell^2)^{\frac{\gamma}{\gamma-1}}$. This relationship for a specified surface temperature T_d (consequently, for specified $p_s(T_d)$) defines the Mach number M_ℓ, the vapor pressure at the outer boundary of the Knudsen layer p_ℓ, and by Eq. (3), the dimensionless pressure at the drop surface $\pi_d(T_d)$. We will also note that for $T_d \gtrsim 397$ K the number $M_\ell = 1$, $f_p(1) = 0.243$, $f_t(1) = 0.813$. Since in the given case the thermal conductivity of the water is insignificant, it is natural to assume that the drop temperature is independent of coordinate r (this assumption is invalid only in a narrow layer near the drop surface of thickness $\delta \sim r_0/\mathrm{Pe}$). In this case the density (and specific volume) of the water are also independent of coordinate r. The water velocity for such homogeneous thermal expansion will be proportional to coordinate r and the rate of density decrease, as follows from the local mass conservation equation (1.1):

$$u = -\frac{r}{3\rho}\frac{d\rho}{dt} = \frac{r}{3\varphi}\frac{d\varphi}{dt}. \tag{4}$$

The integral law of conservation of drop mass for varying radius $r_d(t)$ can be written in the physical variables (decrease in water mass equal to total vapor flux through the area of the drop surface):

$$-\frac{\partial}{\partial t}\left(4\pi\int_0^{r_\text{к}}\rho r^2 dr\right) = 4\pi r_d^2 j_v \quad \text{or} \quad \rho_d\left(u_d - \frac{dr_d}{dt}\right) = j_v. \tag{5}$$

Here $j_v = \rho_\ell u_\ell = M_\ell p_\ell\sqrt{\gamma\mu/(RT_\ell)}$ is the specific vapor flow rate from the drop surface; u_d is the water velocity at the drop surface. In dimensionless form Eq. (5) appears as

$$\frac{dr_d}{dt} = u_d - Q\varphi_d M_\ell\frac{\pi_\ell}{\sqrt{\tau_\ell}}, \quad Q = \frac{p_{cr}h_{cr}}{r_0 q_0}\sqrt{\frac{\gamma\mu}{RT_{cr}}}. \tag{6}$$

The integral law of energy conservation for the drop can be written in the physical variables (change in total drop enthalpy equal to total energy supplied to drop from distributed thermal source q(t), after subtraction of total thermal flux of vapor through drop surface):

$$\frac{\partial}{\partial t}\left[4\pi\int_0^{r_d}\rho H r^2 dr\right] = \frac{4}{3}\pi r_d^3 q(t) - 4\pi r_\ell^2\rho_\ell u_\ell H_\ell. \tag{7}$$

Here $H = h + u^2/2$, $H_\ell = h_\ell + u_\ell^2/2$ are the total specific enthalpies of the water (within the drop) and vapor (at the outer boundary of the Knudsen layer). The last term on the right side of Eq. (7) neglects the thermal flux due to thermal conductivity and viscosity of the vapor, since the vapor velocity u_ℓ is of the order of the speed of sound. Using mass conservation equation (5) and the definition of the latent heat of evaporation $L = h_s - h_d$, where h_s is the vapor enthalpy in the saturated state and h_d is the enthalpy of the water in the drop (both at the temperature of the drop surface T_d), dimensionless equation (7) can be reduced to the form

$$\frac{C_p(\tau)}{\varphi}\frac{d\tau}{dt} = \frac{I(t)}{\varphi^2} - \frac{3}{r_d}Q\frac{M_\ell\pi_\ell}{\sqrt{\tau_\ell}}\left\{L + h_\ell - h_s + A_3\frac{\tau_\ell M_\ell^2}{2}\right\}, \tag{8}$$

$$A_3 = \gamma RT_{cr}/(\mu h_{cr}) \equiv \gamma s A_2.$$

The latent heat of evaporation L and enthalpies h_s, $h_\ell = f_t(M_\ell)h_s$ are referenced to h_{cr}, the specific heat of water at constant pressure C_p, to the ratio h_{cr}/T_{cr}. The last term on the right side of Eq. (8) neglects the specific kinetic energy of the water $u_d^2/2$.

A difference in the temperature of the drop surface T_d from the temperature T within the drop can have a significant effect on the amount of vapor flow due to the exponential dependence of the latter on temperature. Using Eqs. (7) and (1.3), it is simple to obtain the following expression for the temperature gradient in the water near the drop surface:

$$-\lambda \left.\frac{\partial \tau}{\partial r}\right|_{r=r_d} = \mathrm{Pe}\,\omega(\tau_d),$$

$$\omega(\tau_d) = QM_\ell \frac{\pi_\ell}{\sqrt{\tau_\ell}} \left[L + h_\ell - h_s + A_3 \frac{\tau_\ell M^2_\ell}{2} - A_1 \frac{u_d^2}{2} \right] + A_2 \frac{r_d}{3} \frac{\partial \pi_d}{\partial t}. \tag{9}$$

It has been considered here that the vapor thermal conductivity coefficient is significantly less than that of the water [9]. We will also note that the coefficients A_i are small: $A_1 \ll A_2 \simeq 0.0332$; $A_3 = 0.190$, so that the corresponding terms can usually be neglected. We will not define the surface temperature. Near the drop surface we introduce an expanded coordinate $Y = (r_d - r)/\varepsilon$, $\varepsilon \ll 1$. From the equation of conservation of mass, Eq. (1.1), it follows that in the range considered, to the accuracy of $\sim\varepsilon$ the water flow rate does not depend on coordinate Y: $\rho u \simeq \rho_d u_d$. From the conservation of energy equation (1.3) we find that $\varepsilon = 1/\mathrm{Pe}$, and the water temperature must satisfy the equation

$$\alpha h + \lambda \frac{\partial \tau}{\partial Y} = \omega(\tau_d) + \alpha h_d;\ \alpha = \rho_d u_d. \tag{10}$$

The water enthalpy has a temperature dependence close to linear: $h \simeq h_0 + b_0(\tau - \tau_0)$ ($b_0 \simeq 1.35$ [9]). We will write the solution of Eq. (10):

$$\tau(Y) = (\beta - \omega \exp(-\alpha b_0 Y/\lambda))/(\alpha b_0);\ \beta = \omega + \alpha b_0 \tau_d. \tag{11}$$

Assuming that the temperature τ within the drop (as $Y \to \infty$) is known from the solution of Eq. (8), we obtain an implicit relationship for the surface temperature τ_d:

$$\tau_d = \tau - \omega(\tau_d)/(\rho_d u_d b_0). \tag{12}$$

Calculation results are presented in Figs. 1-4. Figure 1 shows the dependence of π, φ, τ on t for four heat liberation variants. Variant I corresponds to continuous radiation switched on instantaneously, or a pulse if we take I = 0 for t > 1. Variants III and IV were used to model a radiation pulse in [5, 17] and [18] respectively. The constants in the heat libertion laws II-IV were chosen from the condition of constancy of the total energy density: $\int_{-\infty}^{\infty} I(t)dt = 1$. Calculations were performed up to the moment when the absolute instability temperature was attained, a value of T_A = 602-611 K in the intensity range considered. Figure 1 also shows t dependences of π, φ, τ obtained without consideration of the change in water temperature upon approach to the drop surface, i.e., at T_d = T (dash-dot curves). In this case the pressure within the drop is significantly higher, and the rate of change of temperature τ and specific volume φ are lower. In variants II-IV the absolute instability temperature is not achieved over the duration of the pulse ($\tau_A \approx 0.931$). With decrease in heat liberation intensity the drop begins to cool, continuing to evaporate. Thus, the dynamics of drop heating are affected significantly by the heat liberation rate and the form of the pulse I(t), especially its leading edge. Precise determination of the drop surface temperature T_d is important.

Figure 2 shows heating diagrams 1-5 in the planes a) π—φ and b) π—τ, encompassing the entire convective regime: $Q_p \simeq 0.557 < Q < Q_\lambda \simeq 290\text{-}2900$. The thermodynamic diagrams are determined not only by the energy—mass exchange parameter Q, but also the heat liberation rate: the higher the heat liberation rate, the higher lie the functions π(φ), π(τ) (for example, higher for variant I than for II-IV). The absolute instability temperature is reached on the spinodal C, which is specified by the equation $\left.\frac{\partial \pi}{\partial \varphi}\right|_{\tau=\mathrm{const}} = 0$. The spinodal is in the upper boundary of drop existence with regard to the thermodynamic parameters π, φ, τ, although explosive drop destruction can set in earlier due to formation of a water—

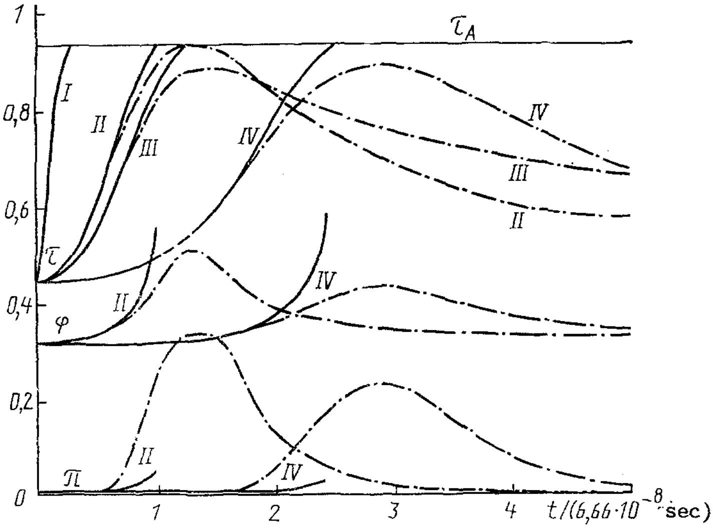

Fig. 1. Dimensionless temperature τ, specific volume φ, and pressure π vs. time for following heat liberation laws: I = $I(t)\equiv1$;

$$II - I(t) = C_2\begin{cases} t/t_2, & 0\leqslant t\leqslant t_2,\\ \exp[-(t/t_2-1)^2/n], & t>t_2,\end{cases}\quad C_2=\frac{2}{1+\sqrt{\pi n}},\ n=2,\ t_2=1;$$

$$III - I(t) = C_3\begin{cases} t/t_3, & 0\leqslant t\leqslant t_3,\\ \exp[-(t/t_3-1)/n], & t>t_3,\end{cases}\quad C_3=\frac{2}{1+2n},\ n=2,\ t_3=1;$$

$$IV - I(t) = C_4\exp[-(t/t_4-3)^2/n],\ C_4=1/\sqrt{\pi n},\ n=2,\ t_4=1.$$

Energy-mass exchange parameter Q = 9.78 ($q_0 = 10^{16}$ W/m^3, r_0 = 1 μm). Solid curves) T_d from Eq. (12); dash-dot curves) $T_d \equiv T$.

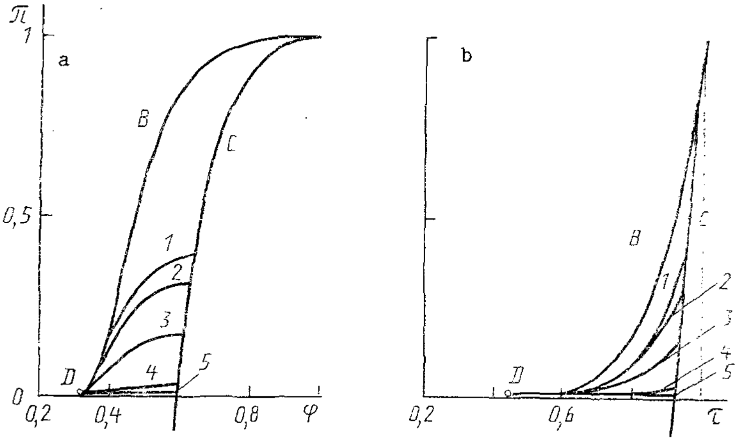

Fig. 2. Water state diagrams during heating in planes: a) $\pi-\varphi$ b) $\pi-\tau$; located in metastable liquid region between binodal (B) and spinodal (C): 1) Q → 0; 2) Q = 0.725; 3) 3.63; 4) 36.3; 5) Q → ∞; D) initial state point (T_0 = 288.15 K, p_∞ = 1 atm, $h_0 = 6.3\cdot10^4$ J/kg, ρ_0 = 999 kg/m^3).

vapor phase transition nucleus within the drop [11]. The mean time of homogeneous nucleus formation t_z can be estimated with the expression (in physical variables):

$$t_z=\frac{J^{-1}}{V_d};\ J=N_1Be^{-G},\ G=\frac{W_*}{kT},\quad V_d=\frac{4}{3}\pi(r_0r_d)^3,\ W_*=\frac{16\pi\sigma^3}{3(p_s-p_d)^2(1-\varphi/\varphi_v)^2}. \tag{13}$$

Here $N_1 \approx 10^{28}$ m^{-3} is the number of molecules per unit volume of liquid; $B \approx 10^{10}$ sec^{-1} is the kinetic factor; k is Boltzmann's constant, V_d is the drop volume; W_* is the work of

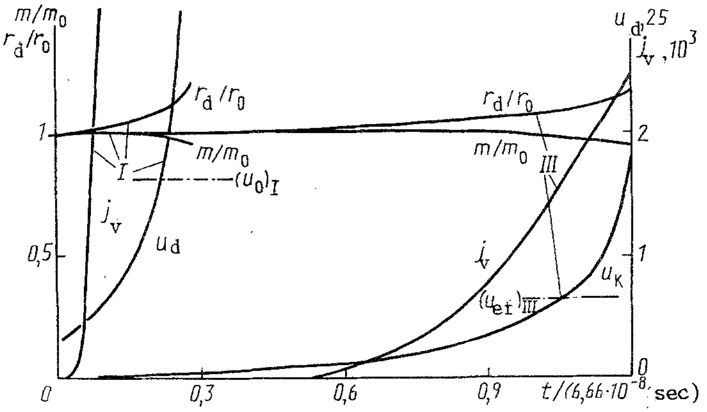

Fig. 3. Drop radius r_d/r_0, mass m/m_0, water velocity u_d at surface, and vapor flow rate j_v vs. time up to explosion (solid curves) for heat liberation laws I and III (see notes to Fig. 1). Energy–mass exchange parameter $Q = 3.63$ ($q_0 = 10^{16}$ W/m³, $r_0 = 2.7$ μm, $m_0 = 8.24 \cdot 10^{-14}$ kg). Dash–dot lines, levels of characteristic velocity $u_0 = 40.5$ m/sec and $u_{ef} = r_0 q_{ef}/(\rho_{cr} h_{cr}) = 16.4$ m/sec for heat liberation laws I and III, respectively. j_v, 10^3 kg/(m²·sec); u_d, 25 m/sec.

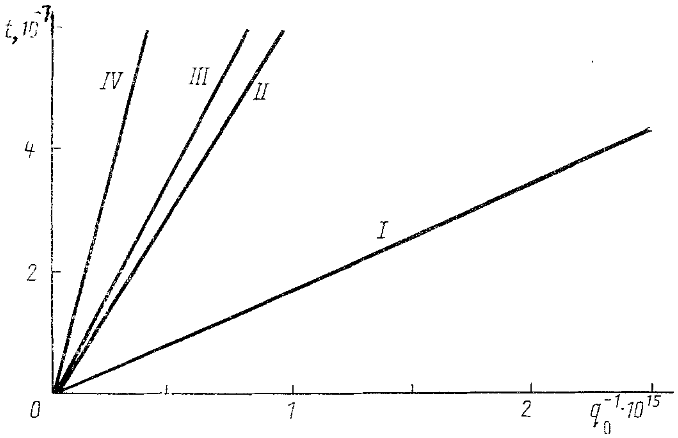

Fig. 4. Explosion time vs. inverse heat liberation intensity q_0^{-1}. t, 10^{-7} sec; $q_0^{-1} \cdot 10^{15}$ W/m³.

critical nucleus organization; σ is the water surface tension coefficient; φ_v is the specific volume of the vapor at temperature T. The last quantity, and thus, the time t_z, has a very intense temperature dependence (several orders of magnitude per degree) and falls off rapidly with increase in water temperature. Explosive drop destruction sets in when the homogeneous nucleus formation time becomes less than the current physical time of the heating process. As would be expected, calculations show that the times of intense nucleus formation are close to the times at which the absolute instability temperature is reached. The differences between these times, a matter of several percent, can be explained by errors in the mathematical model (inaccuracy of the water equation of state (2), or the expression for nucleus formation time (13)).

Figure 3 shows the time dependence of water velocity u_d at the drop surface, vapor flow rate from the surface j_v, drop mass m/m_0 and radius r_d/r_0. Due to thermal expansion the drop radius increases by 15-20%, while the drop mass decreases by several percent by the time of explosion. The drop explosion temperature $T_{ex} \approx 585\text{-}603$ K. The drop surface temperature T_d practically coincides with the temperature inside the drop T near the nonisobaric regime ($Q \approx Q_p$) and differs from it by almost 200 K near the thermal conductivity–convective regime ($Q \approx Q_\lambda$). Correspondingly the vapor flow rate comprises $j_v \sim 10$ kg/(m²·sec) for $Q \approx Q_\lambda$ and $j_v \sim 10^3$ kg/(m²·sec) at $Q \approx Q_p$. For heat liberation laws II and III with initial linear segment of intensity growth more accurate regime limits are given by the effective characteristic intensity $q_{ef} = q_0 C_i$ (as well as the velocity $u_{ef} = u_0 C_i$), where C_i is the corresponding coefficient in laws II, III.

The drop explosion times calculated for the physical model described are close to ones established experimentally, ~$(1-4)\cdot 10^{-7}$ sec [17], as shown by the results presented in Fig. 4. For all heat liberation laws considered, to a high degree of accuracy the explosion time depends linearly on the inverse intensity of heat liberation q_0^{-1} (or q_{ef}^{-1}). These results lead to simple relationships for evaluating the explosion time $t_I = \rho_{cr}(h_{ex} - h_0)\langle\varphi\rangle/q_0$, $t_{II,III} = \rho_{cr}/q_0\sqrt{2\langle\varphi\rangle h_{cr}(h_{ex} - h_0)C_i}$ for heat liberation laws I and II, III respectively (in the latter case for the condition that explosion set in on the linear portion of the growth in intensity I(t)). Here $\langle\varphi\rangle$ is some mean value of the dimensionless specific volume of water during the heating process. If we change the formulation of the problem, fixing the characteristic time (pulse duration) and vary the radiation intensity, then for heat liberation laws II, III, as follows from conservation of energy equation (8), the explosion time will be proportional to the quantity $q_0^{-1/2}$.

In conclusion we will note that the approach described above establishes similarity in the problem of drop heating and explosion. In dimensionless variables the results obtained at $r_0 = 1$ μm and $q_0 = 10^{16}$ W/m³ will be identical to the results for $r_0 = 10$ μm and $q_0 = 10^{15}$ W/m³, since the unique similarity parameter $Q \sim 1/r_0 q_0$ will be identical.

NOTATION

t, time; r, coordinate; α, radiation absorption coefficient; q, heat liberation intensity; I, radiation intensity; ρ, density; p, pressure; T, temperature; h, water or vapor enthalpy; ρ_0, p_∞, T_0, h_0, corresponding initial values; ρ_{cr}, p_{cr}, T_{cr}, h_{cr}, corresponding critical values; $\rho = 1/\varphi$, π, τ, dimensionless density, pressure, and temperature of the water; Eu, Re, Pe, M, Euler, Reynolds, Peclet, and Mach number; Q, similarity parameter (heat-mass exchange); u, water or vapor velocity; r_d, drop radius; T_d, drop surface temperature; I(T), heat liberation law (pulse form) over time; J, nucleus formation frequency; G, Gibbs number.

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