Int. J. Heat Mass Transfer. Vol. 35, No. 2, pp. 583–589, 1992
Printed in Great Britain

0017-9310/92 $5.00+0.00
Pergamon Press plc

Thermal and optical processes in shattering water aerosol droplets by intense optical radiation

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(*Received* 29 *January* 1990)

Abstract—The subject of the present theoretical study is thermal and optical processes occurring in heating and explosion of water aerosol droplets by intense optical radiation propagating in the aerosol. A system of equations is formulated to describe the processes of radiation propagation in the aerosol and its interaction with individual droplets. The space–time distributions of parameters are obtained on the basis of a numerical solution of the formulated system of equations. The effect of the intensity and density of the 10.6 μm radiation energy, number of secondary droplets and vapour fraction formed after radiation-induced thermal explosion of droplets on the parameters of the process is considered. Comparison of some numerical results with experimental data is made.

1. INTRODUCTION

IN THE process of continuous optical radiation propagation with the intensity $I \sim 10^1$–10^2 W cm^{-2} in a water aerosol (clouds, fogs), there occurs heating and regular evaporation of single water droplets that absorb radiation energy [1]. The increase in the radiation intensity may result in the thermal explosion of droplets occurring simultaneously with their evaporation.

The study of the thermal explosion of droplets during the propagation of intense optical radiation in a water spray is of great scientific and practical interest. Experimental and theoretical investigation of the heating and explosion of single water droplets by optical radiation pulses was conducted in refs. [2–8]. The propagation of intense optical radiation in a water aerosol with explosion of droplets was studied experimentally in a large number of works, the results of which were correlated in refs. [7, 9–11]. As radiation propagates in a water aerosol, there occurs heating, evaporation and explosion (fragmentation) of droplets as well as the recondensation of steam. The processes are accompanied by a change in the spectral transparency of the aerosol (it becomes clear or opaque) at the wavelengths of the operating and probing radiations. The propagation of radiation with allowance for the burst of droplets was studied theoretically in recently published works [12, 13] where use was made of the assumption that the explosion of droplets took place when the radiation intensity exceeded a certain critical value, based on the initial radius of a droplet without regard for its evaporation during the heating-up time, and that there occurred a quasi-steady evaporation of droplets with the droplet heat-conduction energy losses being roughly taken into account. This appreciably restricts the validity range of the results obtained in refs. [12, 13], the more so that there is no comparison of theoretical results with experimental data.

From the foregoing it is seen that theoretical investigation of thermal and optical processes during the shattering of droplets in the course of optical radiation propagation in a water aerosol, without invoking the said approximation, is of particular interest and is carried out in the present work.

2. STATEMENT OF THE PROBLEM

The reason for the thermal explosion of a droplet which absorbs radiation energy is an explosive boiling-up of water upon the onset of a metastable superheated state and the attainment of a certain critical temperature T_* with the nucleation of vapour bubbles, their subsequent growth and coalescence. The explosion of the droplet will be considered in the mode of shattering (fragmentation), when, as a result of the explosion, the droplet falls apart into finer (secondary) droplets, and a part of the droplet mass transforms into vapour during the bubble growth.

The process of intense radiation propagation in a water aerosol is a complex set of thermophysical (heating, evaporation and explosion of droplets, recondensation of the vapour generated, etc.) and optical (variation in the optical properties and spectral transparency of the aerosol at the wavelength of operating λ and probing λ_1 and λ_2 radiations) phenomena. In view of this, the influence of the dispersion of secondary droplets, diffusion of vapour and heat from the region of explosion of a single droplet, and of the motion of compression waves in air on radiation propagation will not be taken into account. Moreover, at present the radiation-induced explosion of droplets has not yet been studied adequately: for example there are no data on the sizes and distribution functions of secondary droplets, on the fraction of vapour formed during the explosion, and on the threshold intensities of the explosion of water droplets for wide ranges of the size of droplets, pulse duration,

NOMENCLATURE

- c speed of sound
- c_0 specific heat of water
- c_1 specific heat of vapour
- c_2 specific heat of air
- D coefficient of steam diffusion in air
- $f_0(r_0)$ size distribution function of droplets
- $F(r_0 t)$ function allowing for explosive shattering of droplets
- I intensity of operating radiation
- I_i intensity of probing radiation
- $\bar{j}_\varepsilon$ density of energy flux from particle
- $\bar{j}_{con}$ density of energy flux transported by conduction from particle
- $\bar{j}_m$ vapour mass flux from particle
- K_{ab} effectiveness factor of absorption of operating radiation by particle
- K_{sc} effectiveness of scattering of operating radiation by particle
- K_{0i} effectiveness factor of attenuation of probing radiation by particle
- L_{ev} specific heat of water evaporation
- N_0 concentration of droplets
- N_1 number of secondary droplets formed on explosion
- p pressure
- q_1 mass of vapour released per unit volume per unit time
- r_0 current radius of droplet
- Δr_0 boundary layer thickness
- r_1 radius of secondary droplets
- r_b current radius of bubble
- R_g specific gas constant
- S_0 surface area of droplet
- $\bar{T}_1$ surface temperature of secondary droplets
- T_1 temperature of secondary droplets
- T_m temperature of gas medium
- T_* temperature of explosive boiling-up of water
- T_b water boiling temperature
- T_0 droplet temperature
- $\bar{T}_0$ surface temperature of droplet
- t time
- t_{cir} characteristic time of thermocapillary circulation in droplet
- t_{con} characteristic time of heat conduction in droplet
- t_p duration of radiation pulse
- V_0 volume of droplet
- X spatial coordinate.

Greek symbols

- α_m coefficient of molecular absorption of operating radiation by gas phase
- α_{mi} coefficient of molecular absorption of probing radiation by gas phase
- δ droplet mass fraction evolved as vapour
- κ thermal conductivity of gas phase
- κ_0 thermal conductivity of water
- λ wavelength of operating radiation
- λ_i wavelength of probing radiation, $i = 1, 2$
- ν_0 kinematic viscosity of water
- ρ density of steam–air medium
- ρ_0 density of water
- ρ_1 density of steam
- ρ_2 air density
- σ_0 coefficient of surface tension of water
- χ_0 thermal diffusivity of water.

Subscript

- ∞ initial value.

etc. This leads to the necessity of employing some assumptions and experimental data when constructing the model of radiation propagation in an aerosol during the explosion of droplets.

The system of equations that describes the distribution of the operating ($\lambda = 10.6\ \mu$m) and probing radiations along the X-axis in a polydisperse quiescent water aerosol, taking into account the evaporation and explosion of droplets and imposing the approximation of uniform energy release and temperature throughout the droplet volume, has the form:

$$\frac{\partial I}{\partial X}+\left(\pi N_0\int_0^\infty r_0^2(K_{ab}(r_0)+K_{sc}(r_0))f_0(r_0)\,dr_0+\alpha_m\right)I=0 \quad (1)$$

$$\frac{\partial I_i}{\partial X}+\left(\pi N_0\int_0^\infty r_0^2K_{0i}(r_0)f_0(r_0)\,dr_0+\alpha_{mi}\right)I_i=0 \quad (2)$$

$$\rho_0c_0V_0\frac{\partial T_0}{\partial t}=\frac{1}{4}IK_{ab}(r_0)S_0-\bar{j}_\varepsilon S_0,\quad T_0<T_* \quad (3)$$

$$\frac{\partial(\rho_0V_0)}{\partial t}=-\bar{j}_mS_0 \quad (4)$$

$$4\pi\rho_0L_{ev}r_b^2\frac{dr_b}{\partial t}=\frac{1}{4}IK_{ab}S_0-\bar{j}_\varepsilon S_0,\quad T_0=T_* \quad (5)$$

$$\frac{\partial f_0}{\partial t}+\frac{\partial}{\partial r}\left(f_0\frac{\partial r_0}{\partial t}\right)=F(r_0,t) \quad (6)$$

$$\frac{\partial\rho_1}{\partial t}=\nabla\left(\rho D\nabla\left(\frac{\rho_1}{\rho}\right)\right)+4\pi N_0\int_0^\infty r_0^2\bar{j}_mf_0(r_0)\,dr_0+q_1 \quad (7)$$

$$(\rho_1 c_1+\rho_2 c_2)\frac{\partial T_m}{\partial t} = \nabla(\kappa(\nabla T_m)) + \alpha_m I + 4\pi N_0 \int_0^\infty (\bar{j}_{con}+\bar{j}_m c_1(\bar{T}_0 - T_m)) \times r_0^2 f_0(r_0)\,dr_0 + q_1 c_1 (T_* - T_m) \quad (8)$$

$$p = R_g \rho T = \text{const.} = p_\infty \quad (9)$$

where I and I_i are the intensities of the operating and probing radiations, $i = 1$, $\lambda_1 = 0.63$ μm; $i = 2$, $\lambda_2 = 1.15$ μm; K_{ab}, K_{sc}, K_{0i} are the factors reflecting the efficiency of absorption, scattering of the operating and attenuation of the probing radiations by a water droplet with r_0, N_0 is the number density of droplets; ρ_0 and c_0 are the density and heat capacity of water that depend on T_0 [6], α_m and α_{mi} are the coefficients of molecular absorption of the operating and probing radiations by the gas phase [14]; $f_0(r_0)$ is the size distribution function of the droplets of a polydisperse aerosol;

$$\int_0^\infty f_0(r_0)\,dr_0 = 1, \quad V_0 = \frac{4}{3}\pi r_0^3, \quad S_0 = 4\pi r_0^2;$$

$\bar{j}_m$, $\bar{j}_\varepsilon$ are the densities of the mass and energy fluxes conducted away from the droplet surface in the process of evaporation in the diffusive, when $\bar{T}_0 < T_b$, and gas dynamic, when $\bar{T}_0 > T_b$, regimes [1], where T_b is the boiling temperature of water at atmospheric pressure, $T_b = 373$ K; $T_* = 578$ K is the temperature of the explosive boiling-up of water [15]; r_b the radius of a steam bubble growing in the interior of a droplet at $T_0 = T_*$, $L_{ev}(T_0)$ the specific heat of evaporation of water; $F(r_0, t)$ the function which takes into account the bursting fragmentation of droplets (in the absence of fragmentation $F(r_0, t) = 0$); ρ_1, ρ_2 and $\rho = \rho_1 + \rho_2$ are the densities of steam, air and of the steam–air medium (gas), respectively; c_1 and c_2 are the specific heats of steam and air; T_m the temperature of the medium; κ and D the thermal conductivity of the medium and the coefficient of vapour diffusion in air; q_1 the quantity of vapour formed per unit time per unit volume of the medium on explosion of droplets; $\bar{j}_{con}$ the density of energy flux removed away from the droplet surface by heat conduction in the process of evaporation [1]; p the pressure; R_g the specific gas constant; p_∞ the atmospheric pressure. It should be noted that the characteristic times of diffusion and heat conduction across a radiation beam, having the characteristic dimensions of about 1–10 cm, amount to about 1–10 s $\gg t_p$, and therefore the heat conduction and diffusion can be neglected in this case. The initial and boundary conditions for equations (1)–(9) have the form:

$$t = 0: T_0 = T_\infty; \quad r_0 = r_\infty; \quad f_0(r_0) = f_\infty(r_\infty);$$
$$r_b = 0; \quad \rho_1 = \rho_{1\infty}; \quad T_m = T_\infty; \quad \rho_2 = \rho_{2\infty};$$

$$I(X) = I_0(X=0)\exp\left[-\pi N_0 X \times \int_0^\infty r_\infty^2 (K_{ab}+K_{sc}) f_\infty(r_\infty)\,dr_\infty - \alpha_m X\right];$$
$$I_i(X) = I_{0i}(X=0)\exp\left[-\pi N_0 X \times \int_0^\infty r_\infty^2 K_{0i} f_\infty(r_\infty)\,dr_\infty - \alpha_{mi} X\right]. \quad (10)$$

When $r_0 < \lambda$ the energy release in a water droplet is uniform due to radiation energy absorption, with the uncertainty lying below or being equal to 30% [6]. Moreover, the process of heat conduction and thermocapillary circulation of liquid originating in the droplet with the characteristic times $t_{con} \sim r_0^2/4\chi_0$, $t_{cir} \sim r_0^2/v_0$, where χ_0 is the thermal diffusivity and v_0 the kinematic viscosity of water, at $r_0 = 1$ μm, $t_{con} \sim 7\times10^{-6}$ s and $t_{cir} \sim 5\times10^{-7}$ s lead to an additional equilibration of the temperature T_0 within the droplet. The uniformity of the distribution of T_0 within the droplet is violated only near its surface in the boundary layer with the thickness $\Delta r_0 \ll r_0$ due to evaporation and heat removal from the droplet surface, with the surface temperature being determined from the relation [4]

$$\kappa_0 \frac{T_0 - \bar{T}_0}{\Delta r_0} = \bar{j}_\varepsilon \quad (11)$$

where κ_0 is the thermal conductivity of water in the boundary layer. Since $\Delta r_0 \ll r_0$, the boundary layer volume ΔV_0 is much smaller than the volume of the droplet V_0, $\Delta V_0 \ll V_0$, and with $\Delta r_0 \sim (0.1$–$0.15)r_0$ the error in determining the thermal energy of the droplet, calculated over the entire volume of the droplet with T_0, does not exceed 3–5%. This assumption concerning the uniform distribution of T_0 within the droplet, except for its boundary layer, is confirmed by the agreement between the results for an analogous model of the explosion of droplets and the experimental data of refs. [3, 4]. The authors of ref. [3] observed a symmetric explosion of water droplet with $r_0 \lesssim 12$ μm induced by 10.6 μm radiation pulses. This indicated the equilibration of T_0 within the droplets. When $r_0 \gtrsim 20$ μm, the burst of droplets was asymmetric, acquiring the character of surface explosion with an increase in r_0. Thus, the assumption that T_0 is uniform within the droplet is valid for $r_0 \lesssim 12$–15 μm at $\lambda = 10.6$ μm. When $T_0 = T_*$, a bubble starts forming in the droplet, the dynamics of the growth of which (see equation (5)) agree satisfactorily with the results of refs. [2, 5]. When r_b attains the critical size $r_{b*} = r_0\delta^{1/3}$ [11], the droplet explosions and N_1 identical secondary droplets are formed, as assumed for simplicity. The fraction δ of the droplet mass evolves in the form of steam being generated in the process of the bubble growth. The explosions of bubbles of different sizes result in the formation of a polydisperse system of secondary droplets. In the course of the burst, the mass and energy conservation laws are fulfilled:

$$r_0^3(1-\delta)\rho_0(T_0) = N_1 r_1^3 \rho_0(T_1);$$

$$\frac{1}{3}(r_0^3 - r_{b*}^3)c_0(T_*)\rho_0(T_*)T_* + r_0^2\sigma_0(\bar{T}_0)$$

$$= N_1\left(\frac{r_1^3}{3}c_0(T_1)\rho_0(T_1)T_1 + r_1^2\sigma_0(\bar{T}_1)\right) \quad (12)$$

where r_1 and T_1 are the radius and temperature of secondary droplets, σ_0 the coefficient of the surface tension of water, $\bar{T}_1$ the surface temperature of secondary droplets. After the explosion, the behaviour of the secondary droplets is described by equations (3)–(6). The model takes into account the possibility of the subsequent bursts of secondary droplets and the recondensation (on the droplets) of the steam formed during the explosion. The characteristic lifetime of the region of compression formed during the burst of the droplet with steam liberation comprises $t_x \sim r_0/c$ where c is the speed of sound; when $r_0 \sim 1$ μm, $t_x \sim 3\times10^{-9}$ s. In the case of $t_p \gg t_x$, the condition of the pressure constancy in the channel for radiation propagation can be used (equation (9)). In order to verify the accuracy of the formulated system of equations (1)–(9), the threshold intensities were calculated for radiation with $\lambda = 10.6$ μm that lead to the explosion of droplets with the initial radii $10 \leqslant r_\infty \leqslant 15$ μm, and a satisfactory agreement with the experimental data of ref. [4] was obtained.

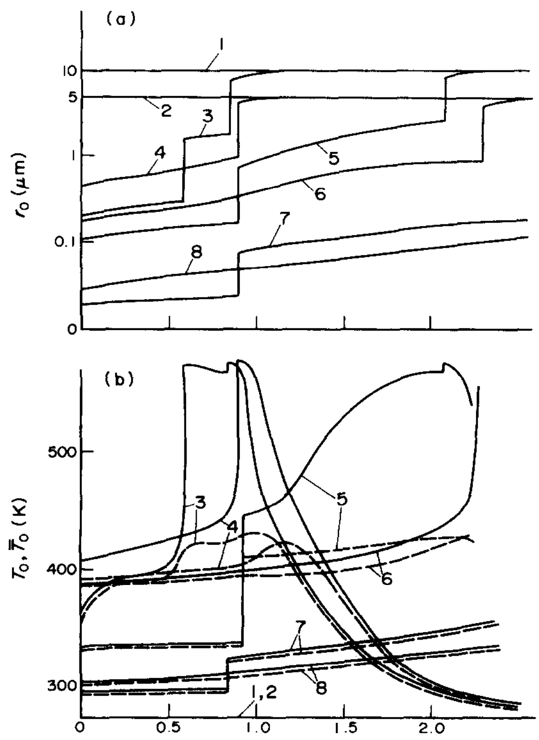

FIG. 1. Distributions of temperatures T_0 (solid lines), $\bar{T}_0$ (dashed lines) and radii r_0 for droplets with initial radii $r_\infty = 5$ (2, 4, 6, 8), 10 μm (1, 3, 5, 7) with respect to ξ at $t = 0$ (1, 2); 6×10^{-6} (3, 4); 1.4×10^{-5} (5, 6); 3×10^{-5} s (7, 8).

3. DISCUSSION OF RESULTS

Calculations were carried out for the propagation of the operating (with $\lambda = 10.6$ μm) and probing (with $\lambda_1 = 0.63$ μm, $\lambda_2 = 1.15$ μm) radiations having the constant intensities I_0 and I_{0i} in a polydisperse water aerosol with the initial function $f_\infty(r_\infty)$ in the form of the Γ-distribution [7] with the most probable radius $r_{pr} = 5$ μm and parameter $\mu = 6$. In order to approximate the given function $f_\infty(r_\infty)$, use was made of a multi-group approximation. In this case the droplets with $r_\infty < 15$ μm were taken into account, since the number of droplets with $r_\infty > 15$ μm and their contribution to water content and radiation attenuation is negligible (below 1%). The initial temperature is $T_\infty = 273$ K. Below, the dimensionless spatial variable ξ will be used which is connected with X as: $X = 1.274\times10^6\xi/N_0$ (in cm), $N_0 = 200$ cm^{-3}. The remaining parameters are taken in a similar manner to ref. [1].

The results of calculations for $I_0 = 10^6$ W cm^{-2}, $\delta = 0.25$, and $N_1 = 100$ are presented in Figs. 1 and 2. From the instant at which irradiation of the aerosol starts, the radiation energy absorption by droplets begins, as well as a rapid growth of T_0 and $\bar{T}_0$ which is accompanied by evaporation and heat transfer of the droplets. When the critical temperature T_* is attained, a vapour bubble starts forming and growing in the interior of the droplet. On the attainment of the explosion condition (certain value of r_{b*}), the droplet explodes. The attainment of the condition of explosion (the instant of explosion) of the droplet is determined by its initial radius and by the dynamics of variation of its radius in the process of evaporation, by the location of the droplet, intensity of operating radiation, initial optical density in the aerosol, etc. With the intensity of radiation exceeding the threshold intensity, primary and subsequent bursts of droplets may occur near the boundary of the aerosol, $X \approx 0$. At the same time, the droplets within the spray that evaporate vigorously under the action of screened radiation, may become so small that, despite the increase in the radiation intensity due to the aerosol bleaching, they may not explode. In the present case, the secondary droplets that had formed after the explosion of the droplet with $r_\infty = 10$ μm, explode once more in the spatial region $\xi \leqslant 0.9$ adjacent to the aerosol boundary. As a result, the wave of the explosion and evaporation of droplets starts propagating into the aerosol with characteristic jumps of r_0 at the fronts of the explosion of droplets with the given r_∞ being due to the explosion-induced shattering of the droplet. The location of the front of the explosion at the given time instant coincides with the position of the temperature maximum in the interior of the droplet $T_0 = T_*$. The distribution of T_0 is charac-

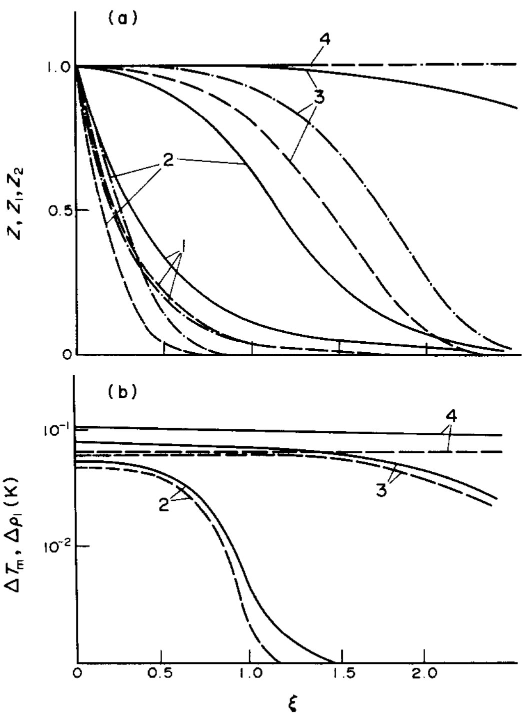

FIG. 2. Distributions of Z (solid lines), Z_1 (dashed lines), Z_2 (dashed–dotted lines) (a) and variations in the gas medium temperature ΔT_m (solid lines) and $\Delta\rho_1$ (dashed lines) (b) with respect to ξ at $t = 0$ (1), 6×10^{-6} (2), 1.4×10^{-5} (3), 3×10^{-5} s (4).

terized by the presence of an abrupt temperature rise in the region of the explosion fronts of the droplets, for which the conditions of explosion are realized, as well as by the presence of a double-wedged profile in the case of the repeated explosion of droplets. When $T_0 < 400$ K, the droplet surface temperature $\bar{T}_0$ differs little from that in the central part of the droplet, $T_0 - \bar{T}_0 < 10$ K. However, as $T_0 \sim T_*$ increases, the temperature difference may attain $T_0 - \bar{T}_0 \sim 150$–170 K, with $\bar{T}_0 \lesssim 420$ K. Figure 2 presents the distribution of the dimensionless energy flux densities of the operating, $Z = I/I_0$, and probing, $Z_i = I_i/I_{0i}$, radiations with respect to ξ for several values of t. As a result of the explosion of aerosol droplets, there occurs a decrease in the transparency of the aerosol by the time instant $t = 6\times10^{-4}$ s at $\lambda_1 = 0.63$ μm, $\lambda_2 = 1.15$ μm when $\xi > 0.4$, and the bleaching of the aerosol at $\lambda = 10.6$ μm and at $\lambda_2 = 1.15$ μm when $\xi < 0.4$. This is due to the different dependence of the factors of attenuation of these radiations on water droplets of different radii. As time proceeds and there occur the explosion and evaporation of droplets, the aerosol bleaches at all the wavelengths as compared with the initial attenuation. However, the degrees to which the aerosol attenuates these radiations differ substantially. Figure 2 presents the distributions of the change in the temperture of the gas medium $\Delta T = T - T$ and in the relative steam density $\Delta\rho = (\rho_1 - \rho_{1\infty})/\rho_{1\infty}$ with respect to ξ for several values of t. In the present case the water aerosol is optically dense, and at the initial time instants $t \lesssim 6\times10^{-6}$ s variations in ΔT_m and $\Delta\rho_1$ are concentrated in the region $\xi < 1$–1.5. In the course of time the changes in ΔT_m and $\Delta\rho_1$ due to the explosion and evaporation of droplets and propagation of the bleaching wave occur virtually uniformly when $\xi \lesssim 2.5$. Note that the changes in ΔT_m and $\Delta\rho_1$ are small as compared with the initial values of T_∞ and $\rho_{1\infty}$, i.e. ΔT_m and $\Delta\rho_1$ exert a weak effect on the process of heating, heat and mass transfer, and on the explosion of droplets.

The predicted and experimental [11] relations for the time dependence of transparency Z (solid line) at $\lambda = 10.6$ μm and Z_1 (dashed line) at $\lambda_1 = 0.63$ μm of a fine-droplet monodisperse (with $r_\infty = 1.3$ μm) water aerosol are given in Fig. 3(a). In this case, the maximum radiation intensity was taken to be equal to $I_0 = 4\times10^7$ W cm^{-2}, the radiation pulse duration to be about 5×10^{-8} s, the number of secondary droplets to be $N_1 = 1.3\times10^3$, and the fraction of vapour to be $\delta = 0.4$ [11]. It is seen that the predicted results agree with the experimental data [11] indicating the validity of the assumptions used in the given model. The spectral transparency of a layer of the aerosol at $\lambda = 10.6$ μm increases sharply after the explosion of droplets, whereas the transparency at $\lambda_1 = 0.63$ μm increases slowly at the expense of the vaporization of

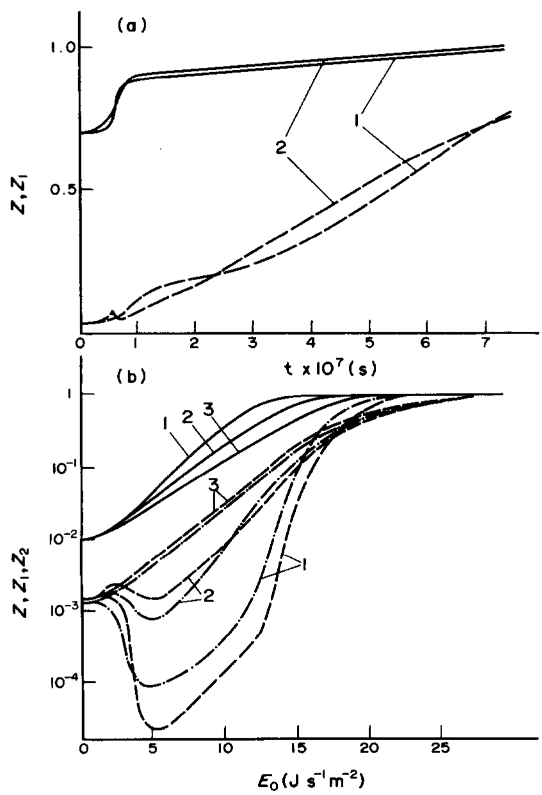

FIG. 3. The dependence of the spectral transparencies Z (solid lines), Z_1 (dashed lines), Z_2 (dashed–dotted lines) of the water aerosol layer, obtained experimentally [10] (1) and predicted (2), on time (a) and with the initial optical thickness $\tau_0 = 4.6$ at 10.6 μm at $I_0 = 10^6$ (1), 10^5 (2), 10^4 W cm^{-2} (3) on the density of operating radiation energy E_0 (b).

secondary droplets by the tail of the radiation pulse. The spike in the transparency at $\lambda_1 = 0.63\ \mu m$ at $t = 5 \times 10^{-8}$ s is explained by the evaporation of droplets occurring before the explosion and leading to the bleaching of the aerosol at λ and λ_1 which is replaced by dimness at λ_1 at the time instants immediately after the explosion.

The investigation was also concerned with the influence of the intensity of radiation I_0 on the change in the spectral transparency of the water aerosol layer. Figure 3(b) presents the dependence of the spectral transparency Z, Z_1, Z_2 (dashed–dotted line) of the aerosol layer with the Γ-distribution initial function, most probable radius $r_{pr} = 5\ \mu m$, parameter $\mu = 6$, and with the initial optical thickness $\tau_0 = 4.6$ at $\lambda = 10.6\ \mu m$ on the energy density $E_0 = I_0 t$ for several values of I_0 at $\delta = 0.25$ and $N_1 = 100$. When $I_0 = 10^4$ W cm^{-2} (equation (3)) the droplets of the aerosol evaporate without explosion and the spectral transparency of the aerosol layer at λ, λ_1, λ_2 increases monotonically with E_0 up to complete clarification. At $I_0 = 10^5$ W cm^{-2} (equation (5)) a single explosion of droplets with $r_\infty \gtrsim 7.5\ \mu m$ is observed, whereas for droplets with $r_\infty < 7.5\ \mu m$ there occurs regular evaporation of droplets without explosion. It should be noted that initially, when the droplets evaporate without explosion, there occurs some increase in transparency, which, after the start of droplet explosions, is replaced by the aerosol dimming at λ_1 and λ_2. At $I_0 = 10^6$ W m^{-2} (equation (5)), the droplets evaporate little before the start of the explosions, and therefore there is virtually no increase in the transparency at the start of irradiation. Here, one observes the explosion of droplets of all sizes well inside the aerosol, whereas the droplets with $r_\infty > 5\ \mu m$ undergo repeated explosions. In this case, the aerosol layer dims greatly, λ_1 and λ_2, and bleaching appears with the passage of a certain period of time in the intense evaporation of droplets after the termination of explosions. At $\lambda = 10.6\ \mu m$ the transparency of the aerosol layer increases monotonically with $E_0(t)$ up to the onset of complete bleaching when $E_0 \sim 20$–25 J cm^{-2}. It should be noted that the bleaching of the aerosol with the explosion of droplets occurs more efficiently and the transparency is 2–3 times higher (when $E_0 \sim 8$–16 J cm^{-2}) than in the case of regular radiation-induced evaporation of droplets. At $\lambda_1 = 0.63\ \mu m$ and $\lambda_2 = 1.15\ \mu m$, first the dimming of the aerosol is observed, and the higher the greater is E_0, which, with an increase in $E_0(t)$, is replaced by bleaching, with the transparency at the final stage at λ_1 and λ_2 turning out to be higher at $I_0 = 10^6$ W cm^{-2}.

Also investigated was the effect of the vapour fraction δ and of the number of secondary droplets N_1, formed in the explosion of droplets, on the transparency of the water explosion layer. The results of calculations are given in Fig. 4. The decrease in the vapour fraction δ at N_1 and other parameters being constant leads to a more rapid explosion of droplets and to an increase in the size of secondary droplets that in turn can explode. This leads to a substantial increase in the dimming of the aerosol at long waves of probing radiations. The vapour fraction δ influences little the transparency of the aerosol: the rise in δ somewhat increases the transparency, since the water content of the aerosol decreases in explosion, while the quantity of vapour increases. When N_1 becomes higher and δ remains constant, the secondary droplets become smaller, and, since the efficiency of the radiation-induced evaporation of fine droplets is lower than that of larger droplets, this leads to a stronger and longer dimming of the aerosol layer at λ_1 and λ_2. The influence of N_1 on the transparency at $\lambda = 10.6\ \mu m$ is also small. The foregoing results indicate that the variation of the parameters δ and N_1, within rather wide limits of $\delta = 0.1$–0.4 and $N_1 = 50$–150, does not virtually alter the transparency of the aerosol at $\lambda = 10.6\ \mu m$ and influences the transparency at $\lambda_1 = 0.63\ \mu m$ and $\lambda_2 = 1.15\ \mu m$.

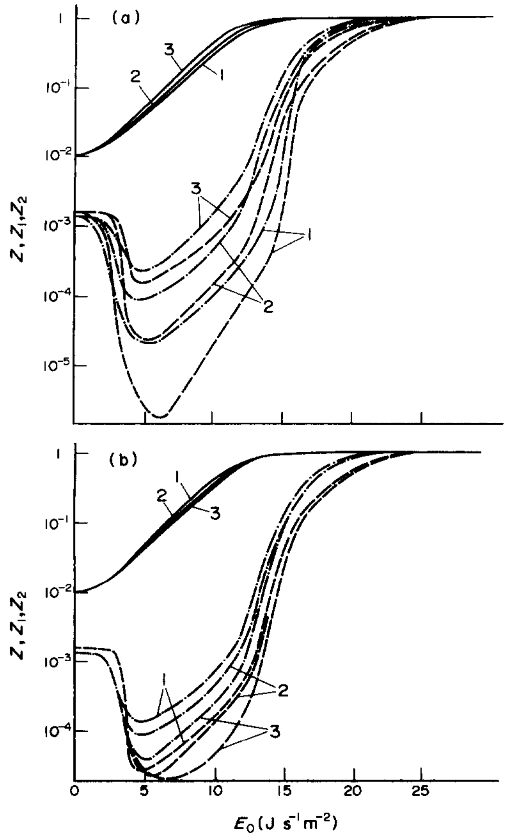

Fig. 4. The dependence of Z (solid lines), Z_1 (dashed lines), Z_2 (dashed–dotted lines) of the water aerosol layer with $\tau_0 = 4.6$ at $\lambda = 10.6\ \mu m$ on E_0 at $I_0 = 10^6$ W cm^{-2}, $N_1 = 100$, $\delta = 0.1$ (1), 0.25 (2), 0.4 (3) (a) and $\delta = 0.25$, $N_1 = 50$ (1), 100 (2), 150 (3) (b).

Thus, based on the methods of mathematical simulation, the thermal and optical processes have been investigated that occur in the course of the explosion of water aerosol droplets on exposure to intense optical radiation, and a satisfactory agreement with experimental data has been obtained.

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MECANISMES THERMIQUES ET OPTIQUES DANS DES GOUTTELETTES D'AEROSOL D'EAU SOUMISES A DES RAYONNEMENTS OPTIQUES INTENSES

Résumé—On étudie théoriquement les mécanismes thermiques et optiques qui apparaissent dans le chauffage et l'explosion des gouttelettes d'aérosol d'eau par la propagation d'un rayonnement optique intense dans l'aérosol. Un système d'équations est formulé pour décrire les mécanismes de propagation du rayonnement dans l'aérosol et son interaction avec des gouttelettes individuelles. Les distributions espace–temps des paramètres sont obtenues par une résolution numérique du système d'équations formulé. On considère l'effet sur les paramètres des mécanismes de l'intensité et de la densité de l'énergie, du rayonnement à 10,6 μm, du nombre de gouttelettes secondaires et de la fraction de vapeur formèe après l'explosion des gouttelettes. On fait la comparaison de quelques résultats numériques avec des données expérimentales.

THERMISCHE UND OPTISCHE VORGÄNGE IN PLATZENDEN TRÖPFCHEN IN EINEM WASSER-AEROSOL BEI STARKER OPTISCHER BESTRAHLUNG

Zusammenfassung—Es werden die thermischen und optischen Vorgänge bei der Aufheizung und der Explosion von Wassertröpfchen in einem Aerosol infolge starker optischer Bestrahlung theoretisch untersucht. Es wird ein Gleichungssystem formuliert, welches die Vorgänge der Strahlungsausbreitung in dem Aerosol und seine Wechselwirkung mit den einzelnen Tröpfchen beschreibt. Das Gleichungssystem wird numerisch gelöst, wobei sich die räumlichen und örtlichen Verteilungen der Parameter ergeben. Die Abhängigkeit der Prozessparameter von folgenden Größen wird betrachtet: Intensität und Dichte der Strahlungsenergie (Wellenlänge 10,6 μm), Anzahl der Sekundärtröpfchen und Dampfgehalt nach der strahlungsinduzierten temperaturbedingten Tropfenexplosion. Abschließend werden einige Rechenergebnisse mit Versuchsdaten verglichen.

ТЕПЛОВЫЕ И ОПТИЧЕСКИЕ ПРОЦЕССЫ ПРИ ВЗРЫВЕ КАПЕЛЬ ВОДНОГО АЭРОЗОЛЯ ИНТЕНСИВНЫМ ОПТИЧЕСКИМ ИЗЛУЧЕНИЕМ

Аннотация—Теоретически исследованы тепловые и оптические процессы при нагреве и взрыве капель водного аэрозоля в процессе распространения в нем интенсивного оптического излучения. Сформулирована система уравнений, описывающая процессы распространения излучения в аэрозоле и взаимодействия с отдельными каплями. На основе численного решения сформулированной системы уравнений получены пространственно-временные распределения параметров. Рассмотрено влияние интенсивности и плотности энергии излучения с длиной волны 10,6 мкм, числа вторичных капель и доли пара, образующихся при тепловом взрые под действием излучения, на параметры процесса. Проведено сопоставление некоторых результатов численных расчетов с экспериментальными данными.