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STRUCTURE OF AN AXISYMMETRICAL NONSTATIONARY WAVE OF ABSORPTION OF LASER RADIATION IN A TRANSPARENT DIELECTRIC

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Thermal laser breakdown of an initially transparent dielectric and the subsequent formation of a plasma wave of absorption of radiation in it, in contrast to the well-studied analogous phenomena in gases [1], have been studied comparatively little. The reason for this is the large number of physical phenomena occurring, as well as the lack of the exact values of the quantities characterizing the state of the dielectric in the pre and post-breakdown states. A comparison of the experimental results [2, 3], theoretical estimates [4, 5], and one-dimensional numerical calculations [6, 7] indicates that the appearance and propagation of the thermal absorption wave is satisfactorily described by the mechanism of nonlinear heat conduction with the appropriate coefficients of thermal conductivity and absorption of laser radiation. At this stage the main parameters of the absorption wave are determined: the propagation velocity, the average and maximum temperatures, and the thickness of the front. The motion of the plasma formed, the possibility of the occurrence of dissociation processes, the presence of defects which absorb radiation, the effect of the dielectric outside the thermal wave, and some other effects are not studied.

This paper is concerned with the study of the effect of two-dimensionality on the thermal wave in a dielectric within the framework of the physical models developed previously for the one-dimensional and nonstationary cases [4, 6, 7].

The following system of equations was studied numerically:

$$c\frac{\partial T}{\partial t}=\frac{\partial}{\partial x}\varkappa(T)\frac{\partial T}{\partial x}+\frac{1}{r}\frac{\partial}{\partial r}r\varkappa(T)\frac{\partial T}{\partial r}+k(T)q,\quad \frac{\partial q}{\partial x}=k(T)q, \tag{1}$$

where T is the temperature; $\varkappa(T)$ is the coefficient of thermal diffusivity; q is the power density of the radiation; k(T) is the absorption coefficient; and c is the heat capacity of the medium, assumed to be independent of the temperature. The coefficients $\varkappa(T)$ and k(T) were taken from [6]:

$$\begin{gathered}k(T)=k_0+k_1\exp(-E/2T),\ \varkappa(T)=\varkappa_0+\varkappa_1 T\exp(-E/2T),\\ k_0=0.25\ \text{cm}^{-1},\ k_1=5\cdot10^4\ \text{cm}^{-1},\ \varkappa_0=1.5\cdot10^{-}\ \text{W/(cm}\cdot\text{deg)},\\ \varkappa_1=2.9\cdot10^{-4}\ \text{W/(cm}\cdot\text{deg)},\quad E=44000\ {}^\circ\text{K},\ c=3.1\ \text{J/(cm}^3\cdot\text{deg)}.\end{gathered} \tag{2}$$

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The equations (1) were solved for t > 0 in the region $x_2 \geq x \geq x_1$, $r_1 \geq r \geq 0$ with the following initial and boundary conditions

$$T(x, r, 0) = T_0 \exp(-r^2/a^2)/(1 + x^2/b^2), \tag{3}$$
$$q(x_2) = q_0 \exp(-r^2/a^2),$$
$$T(x_1, r, t) = T(x_1, r, 0),\ T(x_2, r, t) = T(x_2, r, 0),$$
$$T(x, r_1, t) = T(x, r_1, 0),\ \partial T/\partial r = 0 \text{ at } r = 0,$$
$$T_0 = 2500^\circ\text{K},\ a = 0.02\ \text{cm},\ b = x_2 = 0.12\ \text{cm},$$
$$x_1 = -0.01\ \text{cm},\ r_1 = 0.015\ \text{cm},\ q_0 = 3.2\ \text{MW/cm}^2.$$

The heat-conduction equation was solved numerically by the method of variable directions by an implicit scheme with second-order accuracy in the spatial and first-order accuracy in the time variables. The coefficients $\varkappa(T)$ and k(T) were computed explicitly. The difference grid was rectangular with 250 and 60 nodes along x and r, respectively. Because of the strong nonlinear dependence of the coefficients on the solution, the time step was chosen from the requirement that the front of the thermal wave move one coordinate step within five time intervals. This condition was determined experimentally in one-dimensional calculations. The equation of radiation transfer along the x axis was assumed at each time step on the boundaries of the working cells, used in the calculation of the heat-conduction equation, and, within the cells the temperature was approximated by a piecewise constant function. A heat source with intensity $q_{i-1/2} - q_{i-1/2}$, where $q_{i-1/2}$ is the power density of the radiation at the boundary of the i-th cell, facing the incident radiation, was added to the heat-conduction equation. Based on the fact that the cells are enumerated in the direction of increasing x and the radiation propagates in the reverse direction, $q_{i-1/2} = q_{i+1/2} \cdot \exp(-k(T_i)dx)$. Along the r axis, $q_{i+1/2}$ were assumed to be constant within each interval dr. The law of conservation of energy was obeyed in the procedure described. The region of the calculation was chosen so that the temperature perturbations would not reach the boundaries on several cells, which enabled satisfaction of the edge and boundary conditions (3) because of the negligibly small values of the coefficients $\varkappa(T)$ and k(T) with fixed initial distributions near the boundaries.

In the problem under study, similarity to the one-dimensional case [6], several stages of the process can be separated. The initial stage is characterized by comparatively slow growth of the maximum temperature and rapid motion of the maximum toward the incident radiation (Fig. 1). At t = 0 the maximum is located at x = 0. The radiation paths are comparable to the entire region of the calculation. As the dielectric is heated, the absorption length of the radiation in it decreases substantially, radiation is trapped by an increasingly smaller region of the plasma formed, and a narrow region with relatively high temperatures — the front of the absorption wave — forms (Fig.2). The wave then emerges into a quasistationary propagation state (Fig. 3). In Figs. 1-4 the units of x and r are equal to 10^{-3} cm, and the unit of time is 10^{-6} sec. The numbers on the isotherms indicate the temperature corresponding to them, expressed in $10^3\,^\circ$K.

Figure 1 shows the isotherms for the time t = 160. The temperature field has the form of paraboloids of revolution; the peak temperature ~7 is shifted relative to the initial position by 60 units toward the source of radiation (located on the right in Figs. 1-4). The thermal wave forms and has a high velocity of propagation only at comparatively low temperatures. By the time t = 256 (see Fig. 2), the wave has almost formed, emerging into the quasistationary state with a propagation velocity of 1.4 m/sec and a maximum temperature of the order of 8. These parameters correspond to the one-dimensional theory, which is a consequence of the fact that the absorption length (of the order of several units at T = 7) is much smaller than the radius of curvature of the front near the symmetry axis. In addition to this lead thermal wave, there is a tendency for a second region of high temperatures, originating near the isotherm 4 at x = 57, to form. By the time t = 360 (see Fig. 3), the secondary thermal wave is appreciably amplified, moving away even further from the symmetry axis. Its velocity is equal to 0.8 m/sec along x and 0.5 m/sec along r; the maximum temperature in it is equal to the temperature in the lead wave. The formation of this structure is explained by the complicated nonlinear two-dimensional propagation of heat due to heat conduction and input of energy from an external source, as well as purely geometrical factors, causing screening of the radiation by the lead part. It is difficult to give a more precise interpretation of this phenomenon.

A severalfold change in the coordinate and time steps did not significantly change the solution obtained, which turned out to be significantly more sensitive to a change in the re-

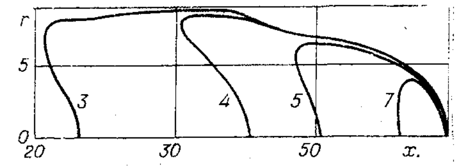

Fig. 1

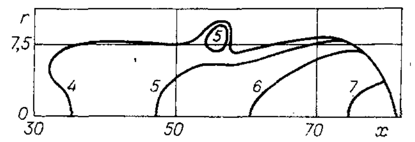

Fig. 2

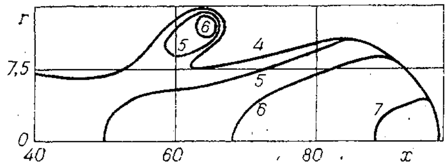

Fig. 3

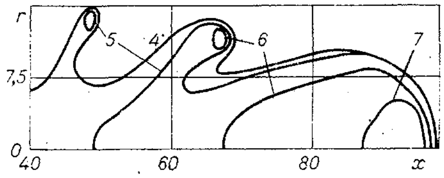

Fig. 4

lations between the quantities $\varkappa_1$, k_1, and q_0. The regions of the parameters in which the appearance of a secondary thermal wave was observed was not determined due to the difficulty of the calculations. Good qualitative agreement was observed between the experimental and computed forms of the entire thermal zone, the propagation velocity of the boundaries of maximum temperature, and their locations relative to the caustic at $x = 0$. It is impossible to make in this case an exact comparison with experiment due to the lack of a complete correspondence between the adopted model for the phenomenon and its actual physical nature, in particular, the lack of parallelism in the propagation of the radiation can decrease the secondary peak and even cause it to vanish.

The calculations performed show that even the simplest physical model produces in the two-dimensional case a very complicated spatial temperature distribution. Factors such as the nonuniformity in the initial temperature distribution, associated with the presence of defects, or the temporal modulation of the radiation (which corresponds to real experiments), can complicate even further the temperature fields. For example, in order to clarify the effect of the last of the factors enumerated, the system (1)-(3) was calculated with q_0 replaced by $q_0(1 + 0.7 \cos(0.2t))$. Figure 4 shows the isotherms for $t = 360$. Modulation of the radiation with this frequency produces corresponding oscillations of the maximum temperature and propagation velocity of the lead thermal wave (whose average values are equal to the values in the variation with constant q_0). In addition, another secondary peak appears at $x = 50$.

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