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INFLUENCE OF ABSORPTION COEFFICIENT FLUCTUATIONS ON THE HEATING OF A WEAKLY ABSORBING MEDIUM BY INTENSE OPTICAL RADIATION

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The problem of heating the opacity fluctuations in a transparent solid medium by powerful optical radiation is numerically solved. The dependence of the absorption coefficient of the medium on the thermoelastic stresses is taken into account.

The need to solve heat conduction and thermoelasticity problems occurs every time in considering the question of destruction of transparent solid media by intense optical radiation. The role of the medium heating processes and the growth of thermoelastic stresses therein are appraised differently by different authors. In clarifying the reasons for the destruction of the optical glass used in lasers, the authors of [1] expressed the hypothesis that heating of the opaque microparticles in the glass and the subsequent growth of the thermoelastic stresses in the medium caused cracks which resulted in a loss of transparency. The idea of transparency inhomogeneities is used somewhat differently in [2-4], in which the importance of taking account of the temperature dependence of the absorption coefficient of the material is assumed. Destruction is caused by the temperature rise in the medium around foreign inclusions heated by the light and by the formation of an absorbing aureole around the impurity particle whose size and temperature grow avalanchelike for a sufficient radiation flux intensity because of nonlinearity of the problem. The role of the thermoelastic stresses, which can, in principle, also result in an increase in absorption by the medium because of narrowing of the forbidden band as the pressure grows, was not taken into account in [2-4]. Still another modification of taking account of the temperature dependences of the absorption coefficient of the medium is presented in [5], in which a medium with a relatively narrow forbidden band and a strong temperature dependence of the appropriate coefficients is examined. The medium here does not contain optical inhomogeneities. The distinction in the approaches listed above indicates the lack of complete clarity in the comprehension of the thermal processes causing the destruction of transparent solid materials by optical radiation and the need for further searches in this area.

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The numerical solution of the following problem is presented in this note. We assume that a transparent solid medium contains a transparency fluctuation (darkening) with dimension 2a. The center of the fluctuation is at the origin. The coefficient of light absorption by the medium $\varkappa$ hence depends on the distance r to the origin and is assumed to have the following form at the initial time

$$\varkappa = \gamma(r)\varkappa_0 = \exp\left\{\left(4 - \left(\frac{r}{a}\right)^2\right)\Theta\left(2 - \frac{r}{a}\right)\right\}\varkappa_0,$$

where $\Theta(x)$ is a step function and $\varkappa_0$ is the absorption coefficient at infinity. Thermoelastic stresses, whose influence will reduce to narrowing the forbidden band, occur in the medium during heating of the inhomogeneities. Taking this narrowing into account, the quantity $\varkappa_0$ can be written in the form $\varkappa_0 = \varkappa_1 \exp\{-(E + \beta\sigma_{rr})/(2kT)\}$ (see [4]), where E is the forbidden bandwidth, σ_{rr} is the radial component of the tensor of the elastic stresses which hence occur, and β is a proportionality factor which can be taken from experiment. The elastic stress tensor can be found from elasticity theory equations, where it will depend on the temperature. It is assumed below that a change in the temperature field occurs more slowly than a change in the field of thermoelastic stresses. This permits considering the temperature quasistationary in solving thermoelasticity problems. This assumption is justified sufficiently well when heating a medium by free laser generation pulses with a duration on the order of 1 μsec. The problem is to solve the heat conduction and thermoelasticity equations for a medium with transparency fluctuations when a powerful light flux is propagated in it.

Analogously to [2], we write the heat-conduction equation in the form

$$\rho c \frac{\partial T}{\partial t} = \chi \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 \frac{\partial T}{\partial r}\right) + I\gamma(r)\varkappa_1 \exp\{-(E + \beta\sigma_{rr})/(2kT)\}, \tag{1}$$

where ρ is the density of the medium; c, its specific heat; χ, its heat conduction; and I, incident light intensity. The equation is written for the spherically symmetric case, i.e., it is assumed that the effect of shade on the inhomogeneities will result in a small correction to the solution. Such an assumption is valid for sufficiently small size inhomogeneities. In conformity with the above, we shall seek the quantity σ_{rr} by means of equations obtained from elasticity theory for a known stationary temperature [6]

$$\frac{\partial}{\partial r}\left(\frac{1}{r^2}\frac{\partial(r^2 u)}{\partial r}\right) = \alpha \frac{(1+\sigma)}{3(1-\sigma)}\frac{\partial T}{\partial r}. \tag{2}$$

Here u(r) is the field of displacements of points of the medium; σ, Poisson's ratio; α, coefficient of volume expansion. The solution of (2) has the form [6]

$$u(r) = \alpha \frac{(1+\sigma)}{3(1-\sigma)}\frac{1}{r^2}\int_0^r r_1^2 (T(r_1) - T_1)\, dr_1,$$

where T_1 is the temperature at infinity. The quantity σ_{rr} can be calculated by means of u(r). Using the known formula

$$\sigma_{rr} = \frac{E_1}{(1+\sigma)(1-2\sigma)}\left[(1-\sigma)\frac{\partial u}{\partial r} + \frac{2\sigma u}{r} - \frac{\alpha}{3}(1+\sigma)(T - T_1)\right],$$

we obtain

$$\sigma_{rr} = -\frac{2E_1\alpha}{3(1-2\sigma)}\frac{1}{r^3}\int_0^r r_1^2 (T(r_1) - T_1)\, dr_1, \tag{3}$$

where E_1 is Young's modulus of the medium under consideration. The initial condition in this case is $T(r) = T_0$. Substituting (3) into (1), we obtain an equation describing the heating of the inhomogeneities and the medium, with the dependence of the absorption coefficient on both the temperature and the thermoelastic stresses which occur taken into account.

The solution of (1) was carried out numerically for the following values of the parameters: $T_0 = 300°K$, $c = 1.3 \cdot 10^3$ J/kg·°K, $\rho = 3 \cdot 10^3$ kg/m³, $a = 5 \cdot 10^{-7}$ m, $p_0 = 10^5$ N/m², $E_1 = 7 \cdot 10^5 p_0$, $\beta = 0.001 \cdot 2kT_0/p_0$, $E/2kT_0 = 30$, $\varkappa_0(t = 0) = 0.25$ m⁻¹, $\chi = 1.3$ W/m·K, $I = 2 \cdot 10^9$ W/m², $\alpha = 0.008/T_0$, $\sigma = 0.22$.

The values of α, σ, E_1, c, χ, and ρ correspond to materials studied in [1]. The value of β is selected approximately by using data available in [7]. The magnitude of the energy gap is selected, to a considerable extent, from considerations of the optimality of the computational scheme and is 1.5 eV for this value of T_0. This is somewhat less than for the materials in [1, 2] but is greater than in [5], for example. Larger values of E result in very acute dependences, whose numerical determination consequently becomes unreliable. Selection of the radiation intensity corresponds to the mean value at which destruction is observed under experimental conditions (see [2]). It should be noted that the aim in these computations is not to obtain a correspondence with a specific experiment since information about the characteristics of actual transparency fluctuations, which is lacking at this time, is needed for such a comparison.

The results of the numerical solution are represented in Figs. 1 and 2. The temperature distribution as a function of the distance to the origin is presented in Fig. 1. Curves 1, 2, and 3 are obtained for the times $t_1 = 0.06 \cdot 10^{-6}$ sec, $t_2 = 0.12 \cdot 10^{-6}$ sec, and $t_3 = 0.18 \cdot 10^{-6}$, respectively. The dashed curves are the result of a computation with the thermoelastic stresses neglected ($\beta = 0$). As follows from the computation, heating of the medium at infinity is very much less than heating near the inhomogeneity; hence, the condition $T_0 = T_1$ is satisfied with good accuracy. The rate of the temperature rise at the origin is substantially higher for the curves 1, 2, and 3 than for the dashed lines and indicates the explosive heating of the center of the inhomogeneity for the selected parameters of the problem. Let us especially note that taking account of the thermoelastic stresses turns out to be quite essential.

The behavior of the radial component of the elastic stress tensor as a function of the distance to the center is shown in Fig. 2. The times for the curves 1, 2, and 3 are the same as for the temperature. The rate of the stress growth indicates the possibility of reaching critical values relative to destruction of the material in the time ~1 μsec exactly as for the temperature. This can be seen from the following simple estimate. The addition to the initial temperature at the center is more than doubled in the time 0.06 μsec, i.e., the temperature rises 2^{10} times up to t = 1 μsec (naturally, destruction occurs earlier).

Therefore, the calculation results presented confirm the realness of this breakdown mechanism and the destruction of transparent materials with characteristics similar to those used in this paper.

NOTATION

t, t_1, t_2, t_3, times; r, r_1, radial coordinates; $\varkappa$, $\varkappa_0$, $\varkappa_1$, absorption coefficients; $\gamma(r)$, proportionality factor; a, characteristic dimension; $\Theta(x)$, step function; E, energy gap; β, proportionality factor; σ_{rr}, radial component of the elastic stress tensor; k, Boltz-

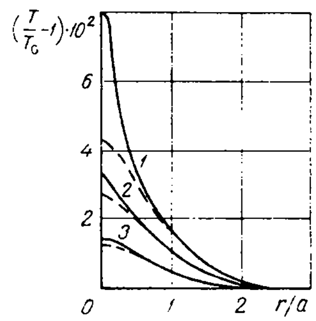

Fig. 1

Fig. 1. Temperature of the medium.

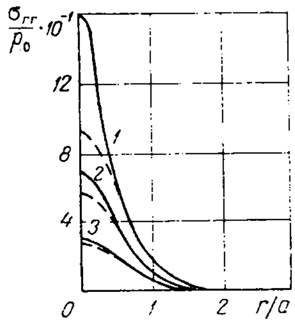

Fig. 2

Fig. 2. Thermoelastic stresses.

mann constant; T, T(r), T_0, T_1, temperatures; I, light flux intensity; u, u(r), displacements of points of the medium; α, volume expansion coefficient; σ, Poisson's ratio; E_1, Young's modulus.

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NUMERICAL INVESTIGATION OF PHOTOABSORPTION CONVECTION IN A HORIZONTAL TUBE.

II. UNSTEADY-STATE CONVECTION

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The establishment of photoabsorption convection in liquids, gases, and plasma subjected to horizontal laser beams of different intensities is investigated by numerical integration of the Navier–Stokes equations in the Boussinesq approximation.

The first part of this investigation [1] was devoted to numerical modeling of steady-state photoabsorption convection. In correspondence with the results of dimensional analysis [2] we obtained three steady-state convection regimes differing in the index of the power in the exponential relation between the free-convection velocity and the laser heating intensity. In the second part of the work we first carried out a numerical investigation of the establishment of the steady state in time. The calculations were conducted by the same method [3] as in Part I.

The establishment times are in good agreement with the estimates in [2]. The processes of establishment of the different regimes differ in their nature: In the case of weak convection all the parameters vary monotonically in time, whereas in the case of developed convection there are considerable oscillations which rapidly decay with time. The effect of modulation of the laser radiation on the establishment process is also considered.

Statement of the Problem. We solve the problem of convective motion caused by absorption, in a long cuvette of rectangular cross section, of laser radiation propagating parallel to the cuvette axis (Fig. 1), which is given by the Navier–Stokes equations in the Boussinesq approximation:

$$\frac{\partial\omega}{\partial t}+\frac{\partial}{\partial x}\left(\frac{\partial\psi}{\partial y}\,\omega\right)-\frac{\partial}{\partial y}\left(\frac{\partial\psi}{\partial x}\,\omega\right)=\Delta\omega+\frac{\partial T}{\partial x},$$

$$\frac{\partial T}{\partial t}+\frac{\partial}{\partial x}\left(\frac{\partial\psi}{\partial y}T\right)-\frac{\partial}{\partial y}\left(\frac{\partial\psi}{\partial x}T\right)=\frac{1}{\mathrm{Pr}}\,\Delta T+qf(x,\ y), \tag{1}$$

$$\Delta\psi=-\omega,\quad u=\frac{\partial\psi}{\partial y},\quad v=-\frac{\partial\psi}{\partial x}.$$

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