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Abstract

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THE INFLUENCE OF THERMAL CONDUCTIVITY ON THE PROPAGATION OF A WAVE OF LASER-RADIATION ABSORPTION

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A powerful flux of laser radiation, falling on the surface of a solid body, leads to strong heating and evaporation of the material. At the first stage of development of the process, the vapors are almost transparent and the main share of the energy is spent on evaporating new portions of the substance ([1,2]). Ionization of the vapors by the laser beam and subsequent absorption of the radiation by the ionized gas may lead to the creation of a high temperature in a narrow zone encompassing a small fraction of the gas mass. In this zone almost the entire radiation flux is absorbed, and evaporation ceases. There arises the so-called absorption flash of laser radiation ([3]). In this case, the gas attains such values of temperature and density that the influence of electron thermal conductivity becomes significant.

1°. Two regimes of propagation of the absorption wave.

The system of gas-dynamic equations in a one-dimensional plane approximation, with account taken of laser radiation and thermal conductivity, has the form

$$\frac{\partial v}{\partial t} = -\frac{\partial p}{\partial m}, \qquad \frac{\partial}{\partial t}\left(\frac{1}{\rho}\right) = \frac{\partial v}{\partial m}, \qquad \frac{\partial q}{\partial m} = -\chi q,$$

$$\frac{\partial \varepsilon}{\partial t} = -p\frac{\partial v}{\partial m} - \frac{\partial q}{\partial m} - \frac{\partial W}{\partial m}, \qquad W = -K\rho\frac{\partial T}{\partial m}, \tag{1}$$

where m is the mass Lagrangian variable, t is time, v is velocity, p is pressure, ρ is density, ε is specific internal energy, T is temperature, q is the radiation-flux density, W is the heat flux, $\chi = \chi(T, \rho)$ is the mass absorption coefficient, and $K = K(T, \rho)$ is the thermal-conductivity coefficient. The gas is regarded as

Fig. 1

Figure 1: Fig. 1

ideal, with equation of state $p = R\rho T$, $\varepsilon = RT/(\gamma - 1)$, where R is the gas constant and γ is the ratio of specific heats.

As initial data, a known distribution of the sought quantities with respect to mass is considered, corresponding to the time at which the flash has already formed and evaporation has ceased. The boundary conditions at the boundaries vapor-vacuum $m = 0$ and vapor-solid body $m = m_1$ have the form

$$q(0,t) = q_0, \qquad p(0,t) = 0, \qquad W(0,t) = 0, \qquad v(m_1,t) = 0, \qquad W(m_1,t) = 0, \tag{2}$$

where q_0 is a constant quantity.

The dependence of the absorption coefficient χ on temperature and density is specified in a form analogous to ([3]):

$$\chi = \beta/(1 + \beta/\alpha_1\rho), \qquad \beta = \alpha_2 \exp(\alpha_3 - \alpha_4/T), \tag{3}$$

where $\alpha_1, \alpha_2, \alpha_3, \alpha_4$ are known constants. The coefficient of electron thermal conductivity K is computed by the method described in ([4]). Problem (1)–(3) is solved numerically by the finite-difference method, the ideas of which are set forth in ([5]).

Analysis and numerical calculations carried out for $K = 0$ showed that, depending on the radiation flux power q_0, the initial temperature formation may propagate in the medium in the regime of an absorption wave or remain stationary on a fixed segment of mass.

At large fluxes (the calculation was carried out for $q_0 = 9.43 \cdot 10^8$ W/cm^2), a sharp rise of temperature over a small segment of mass is accompanied by the emergence of a compression wave, which turns into a shock wave. The shock wave that is formed absorbs the radiation and turns into a wave of the detonation type, which was investigated in ([3]). The detonation wave, shielding the solid body from the radiation, moves against a background of decreasing density and pressure toward the vacuum. The amplitude of the wave in temperature increases as it approaches the vacuum, while the pressure and density behind the wave front decrease. The character of the process in this case is illustrated by Fig. 1, which shows profiles of the temperature function with respect to mass for different instants of time.

Fig. 1

For the flux $q_0 = 0.5{\cdot}10^8$ W/cm^2, an entirely different picture of the development of the process arises. The rise in temperature leads to a strong drop in density in the flash zone. A shock wave is not formed. The initial temperature layer remains stationary on a fixed segment of mass. Owing to the presence of a nonlinear relation between the absorption coefficient $\varkappa$ and the temperature T, the temperature in the layer increases sharply with time.

The presence of electronic thermal conductivity leads to heating of the background in front of the high-temperature formation. In the heated segments of mass the radiation is absorbed. The temperature layer no longer remains immobile. An absorbing temperature wave propagates toward the vacuum, capturing new segments of the gas mass (see Fig. 2).

The velocity of the temperature wave is considerably less than the velocity of the detonation wave described above. Therefore the temperature-wave regime has an advantage in terms of the duration of the vapor-shielding action.

Investigation of the absorption wave in the regime of a detonation wave shows that thermal conductivity has no noticeable effect on its propagation. The temperature in the detonation wave moving toward the vacuum in most cases does not exceed 15 eV, and thermal conductivity is practically insignificant. Its influence appears at later stages of the process, when the shock wave disappears and the temperature near the vacuum reaches high values.

Thus, depending on the magnitude of the incident radiation flux and on the temperatures attained in the flash zone, different mechanisms of propagation of the absorption wave are possible—in the form of a detonation shock wave and in the form of a temperature wave. Similar mechanisms in the study of breakdown in a gas were considered in ([6]).

2. Thermally conductive structure of a detonation shock absorption wave. The structure of the shock absorption wave without taking thermal radiation into account is determined mainly by two processes:

by absorption of the incident laser radiation and by electronic thermal conductivity. The structure is analyzed on the basis of a mathematical model of traveling waves, i.e., under the assumption that all sought quantities depend only on one variable $s = x + Dt$, where x is the Eulerian variable, $D > 0$ is the constant velocity of the detonation wave. For definiteness it is assumed that the shock wave moves through a cold quiescent gas. Ahead of the wave front the conditions are specified as

$$\rho = \rho_0 \qquad q = q_0, \qquad v = T - W = 0. \tag{4}$$

In the temperature range under consideration the character of the dependence of χ on T is such that up to a certain value $T = T_*$ the function $\chi(T)$ is close to zero. For T greater than, but close to, T_*, χ increases sharply with temperature up to some value χ_0, and thereafter, as T increases, differs little from the constant $\chi = \chi_0$. Therefore, to simplify the investigation, it is assumed that the absorption coefficient χ may be represented in the form

Fig. 2

Figure 2: Fig. 2

$$\chi = \begin{cases} 0, & \text{for } T < T_*, \\ \chi_0, & \text{for } T \geq T_*, \end{cases} \tag{5}$$

where χ_0 and T_* are determined from the specific forms of the dependence on T.

Fig. 2

The coefficient of thermal conductivity is a power function of temperature and density,

$$K = K_0 T^a \rho^b.$$

The study of the structure of the absorption detonation wave is reduced to consideration of an ordinary differential equation for the dimensionless function of specific volume $\eta = \rho_0/\rho$:

$$\frac{d\eta}{ds} = -\frac{\gamma+1}{2(\gamma-1)} R\rho_0 D \,\frac{[\eta-\eta^+(s)][\eta-\eta^-(s)]}{K(\eta)(1-2\eta)}, \tag{6}$$

where

$$\eta^\pm(s) = \gamma/(\gamma+1) \pm \exp(-\tau/2)/(\gamma+1),$$

$$K(\eta) = K_0 D^{2a} \rho_0^b (1-\eta)^a \eta^{a-b}/R^a, \qquad D = \sqrt[3]{2(\gamma^2-1)q_0/\rho_0}\,,$$

$$\tau = \int_{-\infty}^{s} \chi\, d\Sigma \quad \text{is the optical thickness.}$$

The integral curves of equation (6) in the absorption region are shown in Fig. 3. The behavior of the function η in the transparency region ($s < 0$) is described by equation (6) for $\chi \equiv 0$ and has been well studied. At the point $s = 0$, corresponding to the onset of absorption, the solutions from both regions ($s > 0$ and $s < 0$) "merge." The family of integral curves in Fig. 3 corresponds to different values $\eta(0) = \eta_*$, i.e., to different T_*, since η_* and T_* are related by

$$T_* = D^2(1-\eta_*)\eta_*/R.$$

Fig. 3

Figure 3: Fig. 3

It is seen from Fig. 3 that for $1 > \eta_* > \eta_*^{(1)}$ the integral curves of equation (6) (solid lines) intersect the isocline $\eta^+(s)$ (dashed line), which determines the structure of the wave without allowance for thermal conductivity, and go off to infinity. A shock wave is not formed. The value $\eta_*^{(1)}$ is deter-

determines the limit of validity of the approximation of the absorption coefficient by formula (5).

In the case $\eta_*^{(1)} > \eta_* > \eta_*^{(2)}$, the profiles of the function η are continuous and as $s \to \infty$ tend to the value behind the shock-wave front $\eta_1 = \gamma/(\gamma + 1)$. In the region $\eta_*^{(2)} > \eta_* > 1/2$, only discontinuous solutions are possible, determining the structure of the wave. As in the case of ordinary gas dynamics, the discontinuities are isothermal. In this case the jump can occur only onto the unique curve LMN, which asymptotically tends to the value $\eta = \eta_1$ as $s \to \infty$. This curve is a separatrix passing through the singular point M. In Fig. 3 the jump is shown by a dash-dotted line.

Fig. 3

Thus, in contrast to the heat-conducting structure of a strong gas-dynamic shock wave, in which the gas-dynamic quantities always undergo a discontinuity, in the heat-conducting structure of a strong absorption shock wave both discontinuous and continuous solutions occur.

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Note: Figure translations are in progress. See original paper for figures.