THE PHENOMENON OF A FLASH OF ABSORPTION OF LASER RADIATION AND THE GAS-DYNAMIC EFFECTS ASSOCIATED WITH IT

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Abstract

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G. G. VILENSKAYA, I. V. NEMCHINOV

THE PHENOMENON OF A FLASH OF ABSORPTION OF LASER RADIATION AND THE GAS-DYNAMIC EFFECTS ASSOCIATED WITH IT

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Under the action of a flux of laser radiation incident on an opaque solid body, a thin surface layer of the substance is rapidly heated and evaporates. The vapor weakly absorbs the radiation. The radiation penetrates through the evaporated and expanded layer of substance into deeper layers, causing their heating, evaporation, etc.—an evaporation wave arises ($^{1-6}$). Estimates (^{4}) show that at a small distance from the evaporating surface thermodynamic equilibrium is established between the condensed and gaseous phases. As the vapor expands adiabatically and cools, the mass fraction of vapor x decreases, while the fraction of condensate $1-x$ increases. The condensate absorbs part of the radiation. The energy release due to this absorption prevents further condensation. Such absorption behind the evaporation wave plays a fundamental role in determining the velocity of its propagation. Indeed, neglecting absorption by the vapor, we obtain that the value x_w (the subscript w refers to parameters behind the wave) must satisfy the condition of transparency of the mixture of vapor and condensate behind the wave

$$m_w \varkappa_c (1 - x_w) =\lesssim 1. \tag{1}$$

Here $\varkappa_c(1-x)$ is the mass absorption coefficient of the condensate (the subscript c refers to the condensate), and m_w is the mass of the evaporated layer. Since $\varkappa_c$ is large, usually $x_w \ll 1$. Indeed, $\varkappa_c$ is of the order of $0.3 \cdot 10^5$ cm^2/g (the value for carbon particles, calculated from (7)), whereas already at an energy input $E = 2$ J/cm^2 and heat of evaporation $Q = 4 \cdot 10^4$ J/g (for carbon) m_w exceeds $5 \cdot 10^{-5}$ g/cm^2. Thus, with a sufficient duration τ of the energy input and with sufficiently large E and m_w, condition (1) becomes significant. We note that from this point of view the character of evaporation is unimportant: whether it is surface evaporation (and equilibrium is established through condensation of supersaturated vapor) or bulk evaporation (and equilibrium is established by an increase in the number of bubbles in the superheated condensed phase). It is enough only that during the time τ equilibrium be established at values $x \le x_w$.

Assuming the zone up to $x = x_w$ to be narrow, we shall use the conservation laws

$$p = p_w + \frac{dm_w}{dt}(u - u_w),$$

$$\frac{dm_w}{dt} = -\rho u = \frac{q - q_r}{H}, \qquad H = h + \frac{u^2}{2} + Q, \qquad h = \frac{k}{k-1}\frac{p}{\rho}. \tag{2}$$

Here t is time; u is the velocity of the substance; q is the flux of radiation incident on the front; q_r is the reflected flux; ρ is density; p is pressure; H is the effective enthalpy; h is the true enthalpy of the mixture; k is the effective (“integral”) adiabatic exponent. The quantities k and h can be found from the equation of state of an equilibrium mixture of vapor and condensate.

$$e = e_c(1 - x) + l_g x, \qquad v = v_c(1 - x) + v_g x,$$

$$p = p_g = f(T), \qquad \rho = 1/v, \qquad h = e + pv. \tag{3}$$

Here the index g refers to the gaseous phase; v is the specific volume; e is the internal energy; f is a function describing the dependence of the phase-equilibrium temperature on pressure. At pressures and temperatures below the critical values, one may neglect the change in ρ_c in comparison with the normal density of the solid ρ_0 and regard the vapor as an ideal gas. The value of the effective reflection coefficient $k_r = q_r/q_w$ is known from experimental data or from an analysis of the structure of the evaporation wave. Since the wave moves at subsonic velocity relative to the matter in front of it (a deflagration-type discontinuity ([8])), the pressure p_s is unknown (the index s denotes the parameters in front of the wave–in the solid). If the evaporation wave moves at subsonic velocity relative to the matter behind it, then the parameters on it (for a given value of x_w) are determined from the joint solution of (2) and the gas-dynamic equations themselves. In the particular case where the radiation flux is constant in time, the rarefaction wave is centered and the front of the evaporation wave moves with constant velocity and coincides with one of the characteristics (the Jouguet condition): $dm_w/dt = \rho_w c_w$, $c = \sqrt{\gamma p/\rho}$. Here c is the speed of sound, and γ is the true adiabatic exponent, found by differentiating (3) under the condition $de + p\,dv = 0$.

In this case $u_w = -c_w$, $p_s = p_w(1 + \gamma_w)$, $H = h_w + c_w^2/2 + Q =$

$$= h_w\left[1 + \frac{\gamma}{k}\frac{k-1}{2}\right] + Q.$$

If the heating in the rarefaction wave is neglected, we obtain

$$\frac{p}{p_w} = \left(\frac{\rho}{\rho_w}\right)^{\gamma} = \left(\frac{m}{m_w}\right)^{a}, \qquad \frac{p}{\rho} = \frac{p_w}{\rho_w}\left(\frac{m}{m_w}\right)^{g}, \qquad a = \frac{2\gamma}{\gamma+1}, \qquad g = \frac{2(\gamma-1)}{\gamma+1}. \tag{4}$$

Therefore the work of the expansion forces G is determined as follows:

$$G = p\frac{\partial v}{\partial t} = -\frac{2}{\gamma+1}\frac{p_w}{\rho_w m_w}\left(\frac{m}{m_w}\right)^{g} = -\frac{2}{\gamma+1}\frac{q_w(1-k_r)p_w}{m_w H \rho_w}\left(\frac{m}{m_w}\right)^{g}. \tag{5}$$

As is seen from (5), G decreases only weakly with m and gradually decreases in time. The energy release due to absorption by the condensate behaves in the same way,

$$(\partial q/\partial m)_c = -q_w(1+k_r)\varkappa_c(1-x). \tag{6}$$

It almost compensates the adiabatic cooling. From comparing (5) and (6) we obtain $x \approx x_w$, $\gamma \approx 1$. In (6) one may set $q_w \approx q_0$ (here q_0 is the radiation flux incident on the vapor boundary).

As m_w grows, a time arrives when it is no longer possible to neglect absorption by the vapor itself, caused by weak equilibrium ionization of the vapor. Taking into account the Boltzmann exponential character of the degree of ionization, one may write

$$(\partial q/\partial m)_g = q\varkappa^g \approx q_0(1+k_r)\varkappa_w^g \exp(-b/T + b/T_w). \tag{7}$$

The temperature T decreases with distance from the surface. Therefore $\varkappa^g$ also falls, and the energy release due to absorption by the vapor is greatest near the evaporating surface. The work of the expansion forces changes only weakly with mass. Equalities (5) and (7) are attained first of all not far from the evaporating surface,

$$\frac{p_w}{\rho_w}\frac{1-k_r}{H(1+k_r)} = \varkappa_w^g m_w. \tag{8}$$

After m_w increases so much that (8) becomes satisfied, a local temperature rise will begin, rapidly accelerating, since $b \gg T$. An absorption flash will occur.

The zone of local heating is at the same time also a zone of elevated pressure; therefore a compression wave and a shock wave arise in the vapor,

Fig. 1

Figure 1: Fig. 1

Fig. 2

Figure 2: Fig. 2

moving toward the radiation flux. A comparatively small heating of the vapor in it proves sufficient for the absorption coefficient to increase by more than an order of magnitude. If before the onset of the flash the vapor layer was almost transparent to the radiation up to the evaporation wave (screening of the evaporating surface was practically absent), then now even a comparatively small mass near the shock-wave front is already opaque. The energy-release zone begins to move after the shock-wave front, the wave is strengthened and turns into a detonation wave. Its parameters can be calculated from relations analogous to (9), but with allowance for counterpressure. The gas behind the detonation wave is in a state of approximately single ionization.

Fig. 1.

After the detonation wave emerges at the boundary of the vapor, the radiation will become "trapped" in an outer layer of small mass. Its intense heating and expansion begin; these lead, despite the further increase in the degree of ionization of the vapor, to a decrease in the mean absorption coefficient. A self-consistent heating and rarefaction wave begins to propagate into the substance ([10,11]); however, its leading front does not coincide with the boundary of the evaporation wave. Indeed, from the moment the flash arises, evaporation ceases (which causes a fall of the pressure at the surface of the solid), and the gas-dynamic processes described occur in a layer of constant mass. Ahead of the heating wave, toward the surface of the solid, a shock wave moves; it is reflected from it and returns to the zone of high temperatures and low densities. A rarefaction wave moves toward the surface of the solid. The propagation of the subsequent waves leads to pressure oscillations. As they approach the body, the heating waves gradually decay. The average value of the internal energy in the heating wave is considerably greater than the effective enthalpy of combustion before the onset of the flash. Therefore the velocity of the heating wave is considerably lower than the velocity of the evaporation wave before the flash, and the time required for evaporation to resume substantially exceeds the time of appearance of the "flash."

Fig. 2.

The ideas and estimates set forth above were checked by direct numerical calculations of the corresponding plane nonstationary problem. For the calculations, the results of which are presented below, it was assumed that, on the evaporation wave, $x_w = 1$, $\gamma = k = 5/3$. The dependence of the absorption

Fig. 3

Figure 3: Fig. 3

Fig. 4

Figure 4: Fig. 4

coefficient on temperature in the low-temperature region was described by (7), with $x_g^w = 7 \cdot 10^2$ cm^2/g for $T_w = 1$ eV, $b = I = 12$ eV, while in the high-temperature region (completion of single ionization and beginning of multiple ionization) it was approximated by the expression $\varkappa = A\rho$, where for carbon vapor $A = 4.4 \cdot 10^7$ cm^5/g^2 was adopted.

Fig. 3

In Fig. 1 the distribution of e is shown at various times t for $q_0 = 300$ MW/cm^2. It is seen that at a certain instant a local heating occurs—a flash. This time is (as for the other variants) in good agreement with criterion (8). The propagation of shock and detonation waves is also seen. Figure 2 shows how the heating wave moves toward the surface of the body; Fig. 3 shows the change in pressure p_s at the surface of the body; Fig. 4, curve 1, shows the variation of I/E, where I is the total impulse at the surface, including the adiabatic stage after the source is switched off. There also, curve 2 shows the dependence of I/E, according to the relations given above, without shielding of the surface, and curve 3 according to the self-similar solution ([10,11]). The cross marks the value of E at which the flash occurs, and the circle the value at which evaporation resumes.

Fig. 4

Schmidt Institute of Physics of the Earth
Academy of Sciences of the USSR

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