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VAPORIZATION OF METAL ABSORBING LASER RADIATION

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The problem of vaporization of a light-absorbing metal into vacuum is considered. It is assumed that the density of the light energy flux is not excessively large so that there is no significant absorption of light by the vapor. The expansion of the vapor thus occurs in a centered rarefaction wave. The obtained boundary conditions relate the values of the hydrodynamic variables in the rarefaction wave with the surface temperature of the metal. This is accomplished by an approximate solution of the gaskinetic problem of vapor motion within a thin film directly adjacent to the phase interface. The velocity of the vaporization front, the surface temperature of the metal, the temperature and velocity of the vapor, and the recoil momentum are calculated.

THE problem under consideration concerns the vaporization of metal exposed to laser radiation in the case when the radiation flux is not excessive. This limitation is necessary because radiation absorption by vapor becomes significant when the flux density is high enough; in such a case the motion of the vaporization front and the expansion of the resulting vapor cannot be considered apart from the problem of light absorption. It appears that the range of flux densities for which the vapor absorption of light is insignificant is limited (for the majority of metals and a neodymium glass laser) by the values of $q \sim 10^{16} - 10^{17}$ erg/cm^2-sec. A more precise value can be readily obtained in each specific case when the problem of vapor motion has been solved. In contrast with the papers[1-3] that present the same case of low radiation flux densities, this paper features correct hydrodynamic boundary conditions on the metal surface that allow us to relate the solution of the solid-phase thermal conductivity problem to the gas dynamic problem of vapor motion. This, in turn, permits us to avoid certain arbitrary assumptions contained in the above papers and to obtain more precise formulas for the velocity of vaporization, vapor temperature, surface temperature, and other parameters.

As in [1-3], we consider a single-dimensional case and a time-constant radiation flux. If the vapor is regarded as an ideal gas and the absorption of light in it is neglected, then the expansion of vapor into vacuum is described by a centered rarefaction wave.[4] In this case the solution of the thermal conductivity problem for a metal shows that a stationary (we use throughout this paper a system of coordinates bound to the vaporization front) temperature distribution is established in the metal in a time period of the order of a/v^2 (a is thermal conductivity and v is the maximum velocity of the phase interface). Under stationary conditions on the surface of the metal, the initial vapor velocity in the rarefaction wave is equal to the local sound velocity. It is clear, however, that such condition is not fulfilled rigorously on the metal surface, if only because the velocity distribution of the atoms near the surface is substantially different from the local equilibrium distribution, which completely precludes a hydrodynamic description of motion at the surface. Consequently in the direct vicinity of the vaporizing surface there is a region of several mean free path lengths in which the distribution approaches equilibrium and which should be considered as a discontinuity surface in the hydrodynamic treatment.

The Boltzmann equation must be solved to determine the structure of this region and the values of the hydrodynamic variables beyond the discontinuity. This cannot be accomplished by any mathematically correct procedure. The situation resembles in this case that of a strong shock wave (or rather a "strong rarefaction wave"). As in the problem of the structure of a strong shock wave, we could probably expect that the method of moments with a test function close to the locally equilibrium function[5] will not yield an adequate approximation. More appropriate is the method consisting in the solution of the kinetic equation suggested by Tamm[6] and Mott-Smith[7] in their study of shock wave structure. The special feature of this method is an approximation of the distribution function within the discontinuity region by the sum of distribution functions before and after the discontinuity with coordinate-dependent coefficients. Such an approximation can be acceptable if the region containing the main change of the distribution function is narrow enough.

We write the distribution function in the form

$$f(x, \mathbf{v}) = \alpha(x) f_1(\mathbf{v}) + [1 - \alpha(x)] f_2(\mathbf{v}) \ldots, \qquad (1)$$

where

$$f_1(\mathbf{v}) = \begin{cases} n_0 \left(\dfrac{m}{2\pi k T_0}\right)^{3/2} \exp\left(-\dfrac{mv^2}{2kT_0}\right), & v_x > 0 \\ \beta f_2(\mathbf{v}) & v_x < 0, \end{cases}$$

$$f_2(\mathbf{v}) = n_1 \left(\frac{m}{2\pi k T_1}\right)^{3/2} \exp\left(-m\frac{(v_x - u_1)^2 + v_y^2 + v_z^2}{2kT_1}\right).$$

$\alpha(x)$ is the unknown function that satisfies the conditions $\alpha(0) = 1$ and $\alpha(\infty) = 0$, T_0 is metal surface temperature, and n_0 is saturated vapor density at this temperature. The expression for $f_1(\mathbf{v})$ takes into account the fact that the vaporized atoms have Maxwellian distribution at a temperature equal to the surface temperature.[8] The values of n_1, u_1, and T_1 refer to equilibrium beyond the discontinuity and are related by

$$u_1^2 = \gamma k T_1 / m. \qquad (2)$$

The conservation laws hold within the discontinuity region

$$\int dv v_x f(x, v) = C_1, \qquad \int dv v_x^2 f(x, v) = C_2, \qquad \int dv v_x v^2 f(x, v) = C_3. \tag{3}$$

Relationships (2) and (3) are sufficient for the calculation of flow parameters at the acoustic point. The solution of Boltzmann equation is necessary only to determine the fine structure of the nonequilibrium region and is not required in this case.

By computing the integrals in (3) we obtain a system of equations for the equilibrium distribution parameters:

$$n_0\sqrt{\frac{kT_0}{2\pi m}} = n_1u_1[1+\beta\varphi_1(M)], \quad n_0\frac{kT_0}{2m} = n_1u_1^2\left[\frac{8}{5}+\beta\varphi_2(M)\right], \tag{4}$$

$$n_0\left(\frac{2kT_0}{m}\right)^{3/2} = \sqrt{\pi}\, n_1u_1^3[4+\beta\varphi_3(M)],$$

where

$$\varphi_1(M) = \frac{1}{2}\left(\frac{e^{-M^2}}{M\sqrt{\pi}} - \operatorname{erfc} M\right), \qquad \varphi_2(M) = \varphi_1(M) - \frac{\operatorname{erfc} M}{4M^2},$$

$$\varphi_3(M) = \left(1+\frac{1}{2M^2}\right)\varphi_1(M) - \frac{\operatorname{erfc} M}{M^2};$$

$$\operatorname{erfc} x = \frac{2}{\sqrt{\pi}}\int_x^\infty e^{-u^2}du; \qquad M = \sqrt{\frac{\gamma}{2}}.$$

For the adiabatic index γ we assume the value $^5/_3$ corresponding to monatomic gas, since the equilibrium of the "inert" degrees of freedom (electron excitation and vapor condensation) is established at a distance from the surface that is much larger than the dimension of the region with Maxwellian distribution. We solve the system of equations (4) and obtain: $\beta = 6.29$, $T_1 = 0.67T_0$, and $n_1 = 0.31n_0$. All the remaining hydrodynamic variables at the acoustic point can now be readily computed.

The following are some results presented without detailed computations. The surface temperature is determined by the equation

$$mn_0(T_0)\sqrt{\frac{kT_0}{m}}\left(L + 2{,}2\frac{kT_0}{m}\right) = 3{,}1q,$$

where L is the heat of vaporization of unit mass. The velocity of the vaporization front is determined by the formula

$$v = \frac{q}{\rho(L + w_1 + u_1^2/2)} \approx \frac{q}{\rho(L + 2.2kT_0/m)}$$

that differs somewhat from that derived in [3] without solving the gasdynamic problem. The recoil momentum acting on the metal can be obtained from

$$\frac{p}{Q} = \frac{1{,}69}{\sqrt{L}}\frac{b}{1+2{,}2b^2}$$

where Q is energy absorbed by the metal and $b^2 = kT_0/mL$. We note that the specific momentum p/Q has a maximum at a certain value of radiation flux density. This maximum was observed experimentally in a number of cases (see for example [9]); however, a more detailed comparison with experiment is difficult since the corresponding values of q are usually close to the limit of applicability of this analysis.

According to computation the flow J_- of atoms condensed back on the surface of the metal amounts to approximately 18% of the flow $J_+ = n_0\sqrt{kT_0/2\pi m}$ of the vaporized atoms. Finally we note that the density of vapor at the metal surface is $n(0) = 0.67n_0$; at the same time, the density n_1 at the acoustic point (provided that $T_0 < 0.4mL/k$) exceeds the equilibrium density of saturated vapor. Therefore the kinetics of vapor condensation must be taken into account in the computation of flow in the rarefaction wave. This renders the problem more complex since the flow is no longer a simple centered wave.

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