# STATIONARY REGIME OF RADIALLY SYMMETRIC MOTION OF LASER HEATED VAPORS WITH TEMPERATURE AND IONIZATION NONEQUILIBRIUM TAKEN INTO ACCOUNT

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We study the effect of temperature and ionization nonequilibrium on the parameters of the stationary radially symmetric motion of vapors being vaporized from the surface of a solid by means of radiation from a laser. Calculations are presented for a range of radiation flow densities q from 5 to 200 MW/cm$^2$ and a focussing radius $r_0$ varying from 1 to 0.01 cm. A comparison with the equilibrium theory worked out in [1] shows that over this range of radiation flow densities the critical flow values at which transition takes place from a regime without screening to one with screening are decreased by a factor of 2 to 2.5 when nonequilibrium is taken into account.

A stationary regime of motion of the vapors from a material heated by radiation was considered in [1] for the case of spherical (or cylindrical) symmetry; in this study the radiation absorption coefficient was taken to be constant or varying with temperature and density in a power-law manner, a situation which corresponds to the action of radiation with large flow densities and high vapor temperatures. Conditions were determined for the existence of a stationary regime, the dependence of the mass outflow rate on the value of the pressure at the surface of the solid was ascertained, and the maximum gas temperatures were also determined from the values of the total incident flow of radiation and the sphere radius. It is of interest to consider the solution of this problem, making the same assumptions but including a realistic dependence of the absorption coefficient on the temperature and density. In connection with this, we can even study stationary regimes with fairly low temperatures ($T \approx 2 \cdot 10^4$°K) and radiation flow densities ($q \approx 100$ MW/cm$^2$), i.e., in regions where a transition takes place from a regime without screening to one with screening for $r_0$ in the range from 0.01 to 1 cm. As noted in [2], it is namely in these ranges of radiation flow densities and temperatures that the temperature nonequilibrium has an essential effect on the heating of the vapors, lowering, in the case of [2], the value of $q_c$ at which screening occurs after a given time. An analogous phenomenon must also hold for the stationary regime. Thanks to the temperature nonequilibrium, the values of $q_c$, defined in [2] as the transition values from the regime without screening to that with screening, are reduced.

A detailed description is given in [1] for the system of gas-dynamic equations of the stationary motion and laser heating of vapors in the presence of radial symmetry; the boundary conditions of the corresponding problem are also described in detail in [1].

The radiation absorption coefficient $\varkappa$, which plays a determining role in the development of the gas-dynamic processes of the motion and heating of a material as it absorbs radiation, has, in the region of temperatures corresponding to the beginning and end of the first ionization, a fairly involved dependence on the thermodynamic quantities. For comparatively small degrees of ionization $\alpha$ the principal contribution to the absorption of radiation from a laser with energy of quanta $\varepsilon < I_1$ ($I_1$ is the first ionization potential) is the photoabsorption by excited atoms. As $\alpha$ increases, the retardation absorption of the electrons during interaction with the ions and atoms becomes predominant. The degree of ionization depends very strongly (exponentially) on the temperature, and, in the absence of thermodynamic equilibrium, is determined by the temperature of the electrons. Therefore to properly determine the absorption coefficient under nonequilibrium

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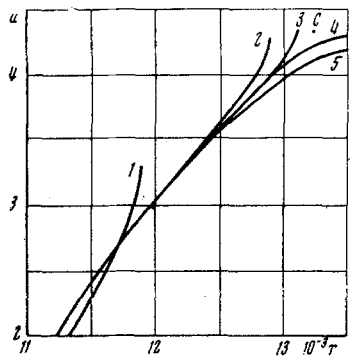


Fig. 1

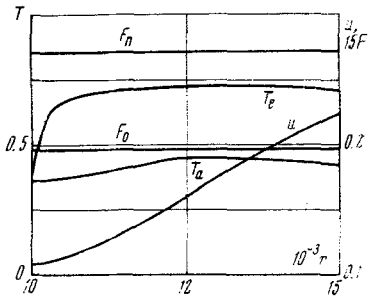


Fig. 2

conditions we must supplement the system of gas-dynamic equations with a system of kinetic equations for determining the temperature nonequilibrium and with a system of equations for establishing the equilibrium values of the degree of ionization and the occupancy numbers of the atomic excitation levels.

We assume that in the nonequilibrium case the enthalpy can be written in the form

$$H = h_e + h_a + \alpha I_1 + \sum_n \beta_n E_n \tag{1}$$

where $h_e = \gamma p_e/\rho(\gamma-1)$ is the enthalpy of the electron gas, $h_a = \gamma p_a/\rho(\gamma-1)$ is the enthalpy of the ion and atomic gas, $\alpha I_1$ is the energy spent on ionization, and $\sum_n \beta_n E_n$ is the energy spent on excitation, where $E_n$ is the excitation energy and the $\beta_n$ are the occupancy numbers of the atomic excitation levels. We introduce the notation

$$h = h_e + h_a, \quad I = \alpha I_1 + \sum_n \beta_n E_n$$

Substituting Eq. (1) into the gasdynamic equations and assuming that the radiation is absorbed only by the electrons and that the ionization and excitation are effected through electron-atom collisions, we obtain a system of equations for determining the temperature nonequilibrium

$$\frac{\alpha}{\gamma-1}\frac{dT_e}{dr} + \left(\frac{T_e}{\gamma-1} + I_1\right)\frac{d\alpha}{dr} + \sum_n E_n \frac{d\beta_n}{dr} + \frac{Q}{u} + \frac{\alpha T_e}{u}\left(\frac{du}{dr} + \frac{2u}{r}\right) = a\frac{F\varkappa\rho}{M}$$

$$\frac{1}{\gamma-1}\frac{dT_a}{dr} + \frac{T_a}{u}\left(\frac{du}{dr} + \frac{2u}{r}\right) = \frac{Q}{u} \tag{2}$$

$$\frac{du}{dr} = u(\gamma-1)\frac{(F\varkappa\rho/M - dI/dr - 2h/r)}{u^2 - (\gamma-1)h} \tag{3}$$

In writing Eqs. (2) and (3) we have adopted the same notation as in [1]; the exchange term is the same as in [2]; $a$ is a dimensional factor depending on the units used in measuring the electron temperature $T_e$ and the temperature of the ions and atoms $T_a$; the adiabatic exponent $\gamma = 5/3$.

The absorption coefficient is determined in a way analogous to that used in [2]; however, the photoabsorption is obtained by summing over the states (hydrogen-like cross sections were assumed) while the population of the levels is determined according to the corresponding kinetic equations. We assumed that the population of a given level is determined by electron impact excitation of the lower levels, by electron impact ionization with the given level and, for levels with binding energy $\varepsilon_n \leq \varepsilon$, by taking into account photoionization by the laser radiation. Cross sections for the corresponding processes were determined in accordance with [3].

The degree of ionization was obtained from the equation

$$\frac{d\alpha}{dr} = \frac{C(T_e, \rho, \alpha)}{u}\left(\frac{\alpha_p^2(1-\alpha)}{1-\alpha_p} - \alpha^2\right) \tag{4}$$

where $\alpha_p$ is the equilibrium value of the degree of ionization.

An increase in the number of equations in comparison with the equilibrium theory leads to a change in the calculational method described in [1]. Solution of Eqs. (2)-(4) was carried out from the surface of the solid ($r = r_0$) to the critical section, but not conversely. We assumed that at the point $r_0$, $T_a = T_e$, $\alpha = \alpha_p$, and that the quantities $\beta_n$ were determinable from a Boltzmann distribution. For a given $r_0$ and a given flow of radiation $F_0$ incident on the surface of the solid, and using also all the constants from the theory of [1] to define the boundary conditions (heat of vaporization $Q_v$, coefficient of reflection $k_r$, etc.), we find

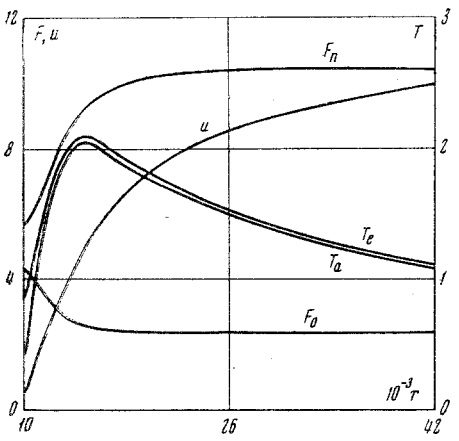


Fig. 3

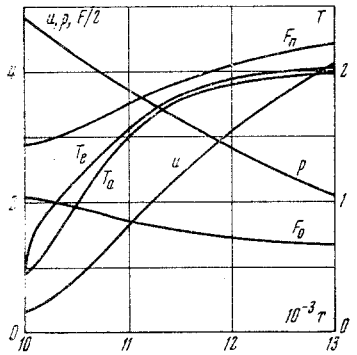


Fig. 4

that the value of one of the gasdynamic quantities ($u_0$ or $\rho_0$) remains indeterminate. This indeterminacy may be removed by requiring the acceleration of the gas to be continuous in passing through the speed of sound; this will hold for a definite value of $u_0$, which we denote by $u_c$. We give the results of our calculations for aluminum (heat of vaporization $Q_V = 10^{11}$ ergs/g, coefficient of reflection $k_r = 0.72$), the energy of the quanta of the incident radiation being $\varepsilon = 1.16$ eV. Henceforth we assume the following units of measure: speed u in km/sec, pressure p in units of 100 bar, radiation flow F per unit solid angle in kW, distance r in cm, and flow density q in MW/cm$^2$.

In Fig. 1 we present the results obtained for u(r) for various values of $u_0$ at the surface of the solid. Curves 1, 2, and 3 correspond to $u_0 > u_c$, curves 4 and 5 to $u_0 < u_c$. The values of $u_0$ for the curves 1, 2, 3, 4, and 5 are 0.340, 0.330, 0.328, 0.327, and 0.325, respectively. The parameters at the sonic point (point C in Fig. 1) were determined by linearly extrapolating all the values from the region where the solutions of type 3 and 4 coincide. From the parameters evaluated at the sonic point we determined the values of all the derivatives (by the method described in [1]) and, by the same token, controlled the accuracy of the extrapolation of values into the sonic point. Using these derivatives we evaluated the outflow at the critical section and continued the calculations from the equations until there was no further change in F; in this way we determined the complete radiation flow to infinity, $F_\infty$.

In Fig. 2 we show the results obtained in calculating the stationary regime for $r_0 = 0.01$ and $q_\infty = 40$ MW/cm$^2$. The incident flow of radiation $F_n$ and the reflected flow $F_0$ show practically no vapor absorption: screening of the surface is absent. The maximum vapor temperatures are of the order of the phase change temperature, and $T_e$ is roughly 0.3 eV larger than $T_a$. The radius of the critical section is $r^* = 0.012$ and the speed at the critical section is $u^* = 0.15$.

In Fig. 3 we show the distribution of the parameters for the same value of $r_0$, but with $q_\infty = 108$ MW/cm$^2$. The vapor temperatures significantly exceed the temperatures at the surface of the solid. The vapors screen the surface from the incident radiation. In Fig. 4, on a much coarser scale, we show the subsonic region. The largest difference of $T_e$ from $T_a$ is observed close to the surface of the body. With an increase of the temperature the difference $T_e - T_a$ decreases. For temperatures T > 0.7 eV we can assume that $\alpha = \alpha_p$ and that the levels are occupied in accordance with the Boltzmann law.

Figure 5 shows how the parameters at the critical section depend on the incident flow $F_\infty$ for $r_0 = 0.01$ cm. As $F_\infty$ increases, the quantities $T^*$, $u^*$, $r^*/r_0$, and $M = u^*/c$ (where c is the sound speed corresponding to the parameters at the solid) all decrease. In Fig. 5 the curves labelled 1, 2, 3, and 4 correspond, respectively, to the quantities $T^*$, $u^*$, $r^*/r_0$, and M. At the point with $F_\infty = 4$, where a regime without screening has been effected, $M \to 1$, the sonic point approaches the solid, and the maximum vapor temperatures become of the order of the phase change temperature. The region with $F_\infty > 4$, but with $F_\infty < 8$, can be interpreted as a region without a stationary regime. Here, evidently, nonstationarity will exist. This regime is of interest both experimentally and theoretically.

Figure 6 shows the distributions $T^*(q_\infty)$ for various values of $r_0$ (curves 1, 2, and 3 correspond, respectively, to the values 0.1, 0.032, and 0.01 cm), calculated with nonequilibrium taken into account (the solid curves) and also in accord with the equilibrium theory (the dashed curves). For $r_0 = 0.1$ cm and $T^* = 4$ eV, the equilibrium theory gives $q_\infty = 140$ MW/cm$^2$, whereas the nonequilibrium theory gives $q_\infty = 55$ MW/cm$^2$. For $r_0 = 0.03$ cm and $T^* = 3$ eV, the equilibrium theory gives $q_\infty = 200$ MW/cm$^2$, whereas the nonequilibrium theory gives $q_\infty = 105$ MW/cm$^2$; and, finally, for $r_0 = 0.01$ cm and $T^* = 2$ eV, the equilibrium value is $q_\infty = 185$ MW/cm$^2$, whereas the nonequilibrium value is $q_\infty = 105$ MW/cm$^2$. On the average, nonuniformity decreases the radiation flow density by roughly a factor of 2 to 2.5. In Fig. 6 we can determine

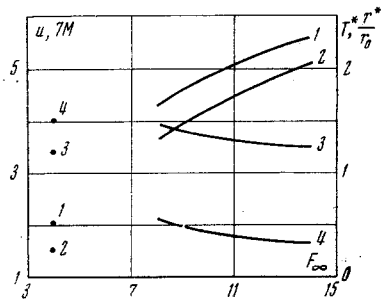


Fig. 5

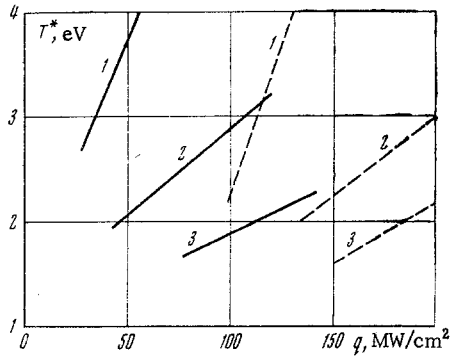


Fig. 6

the critical flow density $q_c$ corresponding to the transition to the regime with effective screening. For $r_0 = 0.01$ cm, $q_c = 80$ MW/cm$^2$; for $r_0 = 0.032$ cm, $q_c = 40$ MW/cm$^2$; and for $r_0 = 0.1$ cm, $q_c = 30$ MW/cm$^2$. We also calculated the maximum values of $q_\infty$ for which a stationary regime may be realized corresponding to values of $r_0 = 0.32$ cm and $r_0 = 1$ cm, $q_\infty = 6$ MW/cm$^2$ and $q_\infty = 4$ MW/cm$^2$.

We note that for flow densities $q < 5$ MW/cm$^2$ the temperature nonequilibrium is small, and zones may appear between the solid and the critical section in which there is a drop in the speed of the vapors. For large q there are no such zones, which may be explained by the fairly large absorption coefficient at the boundary with the solid arising from the temperature nonequilibrium. According to the equilibrium theory these zones exist for considerably large q.

Our calculations show that from the point of view of nonequilibrium processes we may identify, qualitatively, several regions. In the region immediately adjacent to the surface of the solid (on the order of a hundredth part of $r_0$ in extent) temperature and ionization nonequilibrium exists, and occupancy of the levels may differ from the Boltzmann predictions. In the region $T > 0.7$ eV, we have temperature nonequilibrium only; in the region $T > 1.5$ eV, equilibrium may be assumed. In the supersonic portions where cooling of the gas takes place, ionization nonequilibrium may exist, resulting in a "tempering" of the degree of ionization.

To clarify the influence on our calculations of the constants chosen for the impact ionization and the atomic excitation by electron impact, we made calculations in which the constants defining the corresponding cross sections were varied by orders of magnitude (increasing or decreasing). The calculations showed that the solutions of the entire gas-dynamic problem were not very sensitive to such variations. In this connection, the radius of the critical section changed by 20 to 30%. This may be explained by the insignificant extent of the region where ionization nonequilibrium and occupancy of the levels differs substantially from the equilibrium situation.

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