EFFECTS OF NONEQUILIBRIUM OF THE PLASMA OF A VAPOR AUREOLE IN AN INTENSE RADIATION FIELD

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Steady-state radially symmetric motion of the vapors of a small particle of metal, which is vaporized by CO_2 laser radiation, is studied taking into account temperature and ionization nonequilibrium. It is assumed that the vapor is optically transparent. The case of stationary motion of the vapors which completely absorb laser radiation was investigated in [1] neglecting the nonequilibrium. The effect of nonequilibrium on the parameters of the vapor plasma was studied in [2-4]. The stationary radially symmetric motion of vapor heated by radiation was studied for metallic particles, having a radius of 100 μm and longer, for 1.16 eV photons (Nd laser) [3].

In this paper we investigate the vaporization of a small spherical particle of metal (r_0 = 3 μm) exposed to CO_2 laser radiation in the supersonic gas-dynamic regime. We assume that a particle is heated up to temperatures at which the equilibrium pressure is many times higher than the atmospheric pressure, and it can be assumed that vaporization occurs in a vacuum. We shall study the vaporization process in the quasistationary approximation (which is admissible, if the temperature of the particle T_s is much lower than the critical temperature). We assume that the vapor is weakly ionized and practically transparent to the laser radiation. We assume that the plasma vapor weakly absorbs radiation and that this can increase the temperature of the electronic component and hence lead to an increase in the degree of ionization. In the latter case the growth of the specific (per atom) absorbed radiation, which is proportional to the degree of ionization, can increase and, as a consequence, ionization and thermal instability of the plasma in the vapor aureole can develop in the radiation field. In reality these effects are prevented by factors such as cooling of the gas on expansion and losses of energy to recombination reradiation and heating of the heavy (atoms, ions) component of the plasma.

It must be stipulated that under the conditions of intense vaporization, when T_s is significantly higher than the boiling point, breakdown unavoidably arises near a flat surface, the plasma is no longer transparent, and radiation transfer near the surface of the metal must be taken into account. For a particle of radius of several microns, however, the energy losses of the electrons to expansion can be significantly higher than the increase in energy owing to the absorption of radiation. As a result of this, for intensities below the breakdown threshold radiation transfer in the vapor can be neglected and the plasma can be assumed to be weakly absorbing. In addition, effects due to the nonequilibrium of the plasma vapor with respect to both temperature and concentration can also occur.

In order to give a quantitative description of the effects enumerated above we propose the following system of stationary equations [5-7]:

$$nur^2 = n_0 u_0 r_0^2; \tag{1}$$

$$u\frac{du}{dr} = -\frac{1}{m_1 n}\frac{dp}{dr}; \tag{2}$$

$$u\left(\frac{dw_1}{dr} - \frac{1}{n}\frac{dp_1}{dr}\right) = \frac{1}{n}q_{12}; \tag{3}$$

$$u\left(\frac{dw_2}{dr} - \frac{1}{n}\frac{dp_2}{dr}\right) = \frac{1}{n}(\mu J - q_{12} - q_i); \tag{4}$$

$$ud\alpha/dr = k_i\alpha(1-\alpha)n - k_r\alpha^3 n^2. \tag{5}$$

Here Eq. (1) is the integral of the continuity equation; Eq. (2) is Euler's equation; Eqs. (3) and (4) are the equations of energy balance for the heavy component (index 1) and light

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electronic (index 2) component, respectively; Eq. (5) describes the kinetics of ionization and recombination processes in the plasma. In Eqs. (1)-(5) $n = n_+ + n_1$, $n_+ = n_2 = \alpha n$ (n, n_1, and n_+ are the total concentration of heavy particles and the concentration of atoms and ions; n_2 is the electron density; and, α is the degree of ionization), $p = p_1 + p_2$, $p_1 = nkT_1$, $p_2 = n_2kT_2 = \alpha nkT_2$, $w_1 = (5/2)kT_1$, $w_2 = (5/2)\alpha kT_2$ (p, p_1, and p_2 are the total vapor pressure and the pressure of the components of the vapor, T_1 and T_2 are the temperatures of the heavy and light components of the vapor, w_1 and w_2 are the enthalpy of the heavy component and of the electrons per heavy particle [5]), $q_{12} = \frac{3}{2}\left(\frac{2m_1}{m_2}\right)k(T_2 - T_1)\alpha n\nu$ and $q_i = Ik_i\alpha(1-\alpha)n^2 - Ek_r\alpha^3n^3$ are, respectively, the amount of energy transferred from the electronic component into the heavy component as a result of elastic collisions per unit time and the power losses in the ionization–recombination process per unit time; m_1 and m_2 are the atom and electron masses, ν is the frequency of electron–atom and electron–ion collisions; I is the ionization potential; E is the average energy transferred directly to the electrons in one recombination event as a result of collisions of the second kind [7] [under the conditions of the present problem $E \approx (0.2\text{-}0.5)I$]. The rate constants of recombination k_r and ionization k_i are determined by the following expressions [7, 8]:

$$k_r = A/T_2^{9/2}, \quad A = 1{,}05\cdot10^{-8}\ \text{cm}^6\cdot\text{K}^{9/2}\ \ k_i = \frac{\alpha_p^2 n}{1-\alpha_e}k_r; \qquad (6)$$

$$\frac{\alpha_p^2 n}{1-\alpha_e} = 49\cdot10^{14}\frac{g_+}{g_0}T_2^{3/2}\exp(-I/kT_2),$$

where g_+ and g_0 are the statistical weights of the ground states of the ion and atom; α_e is the equilibrium degree of ionization. The expression (6) is Saha's equation [7, 8]. In Eqs. (1)-(5) u is the mass velocity and J is the intensity of the laser radiation. The absorption coefficient of the electromagnetic radiation μ for a weakly-absorbing gas can be found from the formula [7, 9] $\mu = 4\pi e^2\alpha n\nu/m_2c(\omega^2 + \nu^2)$ (e is the electron charge, c is the velocity of light, and ν is the radiation frequency). The effective electron collision frequency ν is equal to the sum of electron–neutral atom collision frequency ν_0 and electron–ion collision frequency ν_+ [7, 8]: $\nu = \nu_0 + \nu_+ = nv_2\sigma_0 + n_2v_2\sigma_+$, $v_2 = (8kT_2/\pi m_2)^{1/2}$. Here σ_0 and σ_+ are the cross sections for elastic collisions of electrons with atoms and ions [7]:

$$\sigma_0 = \pi a^2, \ \sigma_+ = 1.1\pi e^4\Lambda/(kT_2)^2, \ \Lambda = \ln(3(kT_2)^{3/2}/2(4\pi n)^{1/2}e^3)$$

(Λ is the Coulomb logarithm and a is the radius of an atom).

To solve the system (1)-(5) (with unknown functions u, T_1, T_2, n, and α) the boundary conditions following from the Knudsen–layer model [10, 11] with the Mach number $M_0 = 1$ [12] were employed:

$$u_0 = c_0 = (5kT_0/3m_1)^{1/2}; \qquad (7)$$

$$T_0 = 0.67T_S; \qquad (8)$$

$$n_0 = 0.31n_S, \ n_S = n_e(T_S); \qquad (9)$$

$$T_{20} = T_S; \qquad (10)$$

$$\alpha_0 = \alpha_p(T_S, \ n_S). \qquad (11)$$

Here T_S is the temperature of the surface of the particle; $a_e(T_S, n_S)$ is the equilibrium degree of ionization with $T_2 = T_S$, $n = n_S$, determined from the Saha's formula (6); $n_e(T_S)$ is the equilibrium concentration of the vapor at the temperature T_S determined by the Clausius–Clapeyron formula [13]: $n_e(T_S) = (p_{00}/kT_S)\exp\{Lm_1(1/T_{00} - 1/T_S)/k\}$ ($p_{00} = 1$ atm $= 1.013\cdot10^6$ dynes/cm^2, T_{00} is the boiling point, and L is the specific heat of vaporization). The indices 0 and S refer to the values at the exit from the Knudsen layer and on the surface, respectively.

The boundary conditions for the electronic component (10) and (11) require explanation. The small mass of the electrons leads to the fact that their thermal velocity v_2 is at least two orders of magnitude higher than the velocity u of the ordered motion of the gas as a whole. Under these conditions the electron distribution function (in contrast to the distribution function of the heavy particles – atoms and ions) is practically not distorted near the surface of evaporation (in the Knudsen layer), and this means that there is no jump in the temperature T_2 ($T_2 = T_S$). As regards the value of α_0, we start from the fact that it does not depend on the degree of nonequilibrium of the Knudsen layer with respect to the concentration of the heavy component (i.e., on the jump in the concentration n) and should be the same as

in the case of complete equilibrium (in the absence of hydrodynamic flow), when $n_0 = n_S = n_e(T_S)$.

It should be noted that the surface temperature T_S is uniquely related with the radiation intensity J by the equation of energy balance under conditions of stationary evaporation $J\pi r_0^2 K = Lm_1 n_0 c_0 4\pi r_0^2$ (K is the absorption coefficient of the metal particle [14]: $K \approx 4n(n^2 + k^2)^{-1}$, $m = n + ik$ is the complex index of refraction). At high temperatures the estimate $K = 0.09$ ($T_S = 4000$ K) is valid for aluminum. We also note that if we set $p = p_1$ ($p_2 \approx 0$) in Eq. (2) and $q_{12} \approx 0$ in Eq. (3), then the system (1)-(3) can be easily integrated [5, 6]:

$$T/T_0 = 1 - [(u/c_0)^2 - 1]/3; \tag{12}$$

$$n/n_0 = (T/T_0)^{3/2}; \tag{13}$$

$$\frac{r}{r_0} = \left(\frac{c_0}{u}\frac{n_0}{n}\right)^{1/2} = \left[\frac{c_0}{u}\left(1 - \frac{1}{3}\left(\left(\frac{u}{c_0}\right)^2 - 1\right)\right)^{-3/2}\right]^{1/2}. \tag{14}$$

It remains to integrate the two equations (4) and (5) with two unknown functions: T_2 and α. In this approach the effect of the light component of the plasma on the heavy component is adiabatically isolated, and this is what leads to the well-known expressions (12)-(14). The approximate solution obtained in this manner for the system (1)-(5) is close to the exact solution in the entire range of applicability of this system.

The system (1)-(5) with the boundary conditions (7)-(11) was solved numerically in both the complete and simplified variants [with Eqs. (1)-(5) replaced by the approximate equations (12)-(14)] for an aluminum particle with radius $r_0 = 3$ μm, which is vaporized by CO_2 laser radiation with intensity $J \approx (4\cdot10^6\text{-}3\cdot10^8)$ W/cm^2. The results of these calculations are presented in Figs. 1-3 and make it possible to draw the following conclusions.

Under the conditions of intense vaporization of a single particle in a vacuum or a rarefied medium by laser radiation with intensity $J \approx (10^7\text{-}10^9)$ W/cm^2 the electron temperature T_2 virtually always takes off from the temperature of the atoms and ions T_1 (Fig. 1). Here three fundamentally different regimes of radiation action on the aureole are possible.

For comparatively low intensities ($J \lesssim 10^8$ W/cm^2) the losses of energy of the electronic component of the plasma are greater than the absorbed power and T_2 drops off monotonically toward the periphery of the aureole (see Fig. 1: the graph 7 corresponds to $J = 2.5\cdot10^7$ W/cm^2, $T_S = 3600$ K, and the graph 6 corresponds to $J = 9.55\cdot10^7$ W/cm^2 and $T_S = 4200$ K). In this case the degree of ionization α practically everywhere in the aureole remains constant and equal to its value on the surface of vaporization.

At higher intensities ($J = 1.4\cdot10^8\text{-}2.1\cdot10^8$ W/cm^2) the so-called prethreshold regime of radiation action on the aureole is possible. In this regime the absorption in the interior regions exceeds the losses, and at the periphery, owing to the decrease in the density n_2, the absorption drops and the losses start to predominate. For this regime nonmonotonic variation of the electron temperature T_2 is characteristic: The maximum is reached at some distance $r \sim (1\text{-}10)r_0$ from the surface of evaporation and then drops off monotonically as r increases [see Fig. 1, where $J = 1.62\cdot10^8$ W/cm^2 and $T_S = 4500$ K (5), and $J = 2.05\cdot10^8$ W/cm^2 and $T_S = 4650$ K (4)]; in the process, α also increases, and possibly even by several times (Fig. 2, graphs 5 and 4, respectively) in the region where T_2 increases, but when T_2 starts to decrease the ionization process slows down and reaches a constant level at the periphery of the aureole, and the composition of the plasma is quenched (Fig. 3, curve a illustrates the dependence of the relative degree of ionization α/α_0 at the periphery of the aureole at $r/r_0 = 36$ on the radiation intensity; $J_{th} = 2.12\cdot10^8$ W/cm^2 is the threshold intensity).

At still higher intensities ($J \geqslant 2.12\cdot10^8$ W/cm^2 for Al with $r_0 = 3$ μm) the growth of α can compensate the drop in the collision frequency owing to expansion; as a result the relative contribution of absorption per atom exceeds the total losses and T_2 increases monotonically, which results in rapid growth of the degree of ionization (breakdown) near some value of the radius $r = r_b$ (see Figs. 1 and 2, where curve 3 corresponds to $J = 2.15\cdot10^8$ W/cm^2, $T_S = 4680$ K, 2) $J = 2.21\cdot10^8$ W/cm^2, $T_S = 4700$ K, 1) $J = 2.56\cdot10^8$ W/cm^2, $T_S = 4800$ K). The breakdown radius r_b is determined by the intensity J and near threshold it is very sensitive to changes in the intensity (Fig. 3, curve b).

Analysis of the calculations performed showed that in the prethreshold regime studied, only one of the mechanisms of energy loss by the electron component in the aureole is important in practice – the work of expansion of the electron gas [the second term on the left-hand

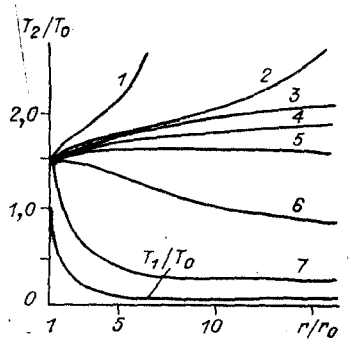

Fig. 1

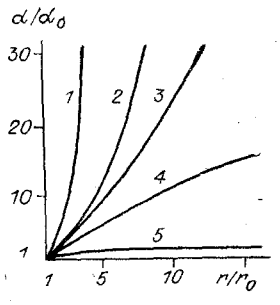

Fig. 2

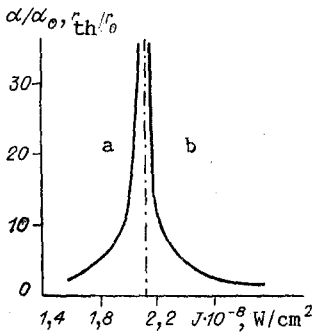

Fig. 3

side of Eq. (4)]. It is the ratio of this work to the absorbed energy and the losses to ionization that determines the position of the threshold of an individual breakdown in the aureole. The heat transfer into the heavy component and losses to recombination reradiation can be neglected. These results remain valid in the aureole in the case of the subthreshold regim ($J < J_{th}$) as well as higher intensities ($J \geqslant J_{th}$) in the regions of the aureole where breakdown has not been reached ($r < r_b$). Under these conditions the heavy component is thermally ($q_{12} \approx 0$) and mechanically ($p_2 \approx 0$) isolated.

This is confirmed by the fact that the numerical solutions of the system (1)-(5) in their complete and simplified variants [see Eqs. (12)-(14)] are practically indistinguishable from one another within the limits of the computational error in the subbreakdown regime. Physically this can be explained as follows: In the subbreakdown regime the electron density is low ($\alpha = n_2/n \ll 1$), and for this reason in spite of the fact that the electron temperature breaks away from the temperature of the heavy particles ($T_2 > T_1$), the enthalpy of the electrons per heavy particle [$w_2 = (5/2)\alpha k T_2$] and their pressure ($p_2 = \alpha n k T_2$) are negligibly small compared with the enthalpy and pressure of the heavy component; this makes the heavy component adiabatically isolated. The smallness of the electron density also makes the plasma transparent, and this makes it possible to neglect the radiation transfer and to set J = const in the aureole, not neglecting, however, the absorption of radiation by the electrons. In the case $\alpha \ll 1$ the absorbed power $\mu J/n$ is too small to attenuate the beam, but it is entirely sufficient for T_2 and α to increase.

The situation changes fundamentally when breakdown is achieved. For intensities $J > J_{th}$ the solution of the system (1)-(5) differs significantly from the adiabatic variant (12)-(14): In the solution of Eqs. (1)-(5) near the breakdown radius $r \approx r_b$ the flow slows down owing to the increase in the electron pressure p_2 and the flow becomes subsonic. This apparently indicates that the solution obtained in the interior region $r < r_b$ is unstable and that the formulation of the problem must be significantly modified, but this falls outside the scope of this work. One can hope, however, that the values obtained here for the breakdown radii (see Fig. 3, curve b) approximately correspond to the position of the absorption wave in the aureole.

For the equilibrium ($T_2 = T_1$) density of the ionized plasma a consistent description of the gas-dynamic and radiation processes for spherically symmetric flows of matter and radiation can be found in [15, 16].

Thus in the case of the vaporization of a small particle the losses due to expansion create the fundamental possibility for the existence of a stable nonequilibrium with respect to the electron temperature and density in the stationary vapor aureole. This regime of interaction of the radiation with the aureole can be called the subbreakdown regime. It was also shown that in the aureole the breakdown of a separate small particle can be achieved.

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DESTRUCTION OF THIN FILMS AND FOILS BY CONTINUOUS SPECTRUM RADIATION

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An explosive source was used in [1] to study the effect of high power UV radiation on aluminum foils. It was shown that failure thresholds of the specimens studied significantly exceeded the sublimation energy because radiation was screened by the vapor evolved. Much data is also available [2] on the action of laser radiation on metal films, according to which, depending on irradiation conditions and the quality of the film preparation, the energy expended in destroying the film can vary from the heat of fusion to the sublimation energy. The goal of the present study is to experimentally determine energy thresholds for destruction of foils and thin films of aluminum and bismuth under the action of continuous spectrum radiation of relatively low power. A high power (up to 200 kA) electrical discharge was used as the radiation source. The experiments were performed in argon and air at normal density. The maximum radiation flux density on the specimen surface comprised ~100 kW/cm^2 with duration up to 100 μsec.

The films used were produced by thermal deposition of metal on glass substrates in a vacuum. The film thickness was determined to an accuracy of 5% by weighing the specimens before and after deposition.

The dynamics of discharge channel growth and the process of specimen destruction were recorded by an SFR-2M high speed camera; uncertainty in velocity and distance measurements was approximately 5%.

The discharge was initiated by electrical explosion of a planar aluminum foil 90 × 70 mm in area and 8 μ thick, located on a dielectric surface. A capacitor bank with net capacitance

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