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RADIATION ORIGINATING BY THE IMPACT OF A GAS LAYER AGAINST AN OBSTACLE AT VERY HIGH VELOCITIES

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UDC 533.6.011

For some time now, various devices that allow gases to be accelerated to very high velocities have been constructed. As an example, we point out the erosion-type magnetoplasma compressors [1-5], in which maximum velocities (70-90 km/sec) with a quite high density of the gas jet are being successfully achieved. Deceleration occurs when this jet impacts against an obstacle and the kinetic energy of the gas is converted into internal energy. As the temperature of the heated gas becomes high, the emission of the plasma can be considerable. This effect has already been used in experiments [4, 5] in order to increase the energy conversion factor of an electric battery, feeding a plasmodynamic discharge, into radiation energy. It will be of theoretical interest to estimate the principle characteristics of the heated gas and the resulting radiation pulse for different jet parameters (velocity, density, and length) which could then be used to find their optimum values.

The pattern of the motion and transfer of radiation in the case of an arbitrarily shaped obstacle and with an arbitrary distribution of the parameters in the jet can be extremely complex, and for its description the time-consuming solution of the two-dimensional nonsteady radiation-gasdynamic problem is necessary. However, in certain cases, this phenomenon can proceed under conditions which are quite close to one-dimensional plane geometry (for example, if the jet impacts on the plane base of an evacuated cylindrical "bucket," as if "cutting out" of it a uniform central part, which occurred in [4], and the times being considered are such that the resulting shock wave traverses a distance which is less than the diameter of the bucket).

We shall carry out some estimates of the parameters of a plasma heated up by the impact against an obstacle. Suppose that the average velocity of the jet is ~50 km/sec and the

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 6, pp. 32-39, November-December, 1978. Original article submitted October 3, 1977.

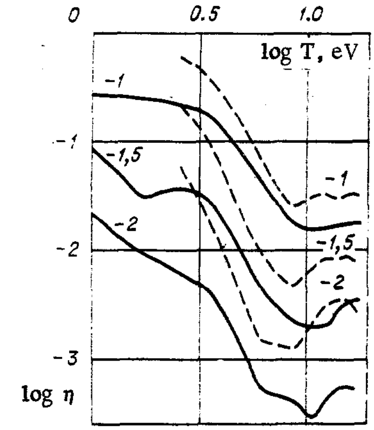

Fig. 1

kinetic energy of unit mass of the gas is, correspondingly, ~10^3 kJ/g. In the shock wave, this kinetic energy will be converted into thermal energy. For definiteness, we shall assume that the material of the jet is aluminum. The thermodynamic properties of aluminum vapor, in the graphical form given in [6], can be approximated by the expression

$$e = 5.4T^{1.90}(\rho/\rho_L)^{-0.154},$$

where e is the specific internal energy, kJ/g; T is the temperature, eV; ρ is the density, g/cm³; and $\rho_L = 1.20 \cdot 10^{-3}$ g/cm³. With a density of the gas advancing on the obstacle of $\rho_s \sim 10^{-5}$ g/cm³ or a density behind the shock wave of $\rho_s \sim 10^{-4}$ g/cm³, we obtain that the temperature reached is $T_s \sim 10$ eV. The density of the gasdynamic flow of energy of the advancing jet $q_h = (1/2)\rho u^3$ in this case amounts to ~10^2 MW/cm², whereas the radiation flux density of a black body is $q_b = \sigma T_s^4 \sim 10^{-3}$ MW/cm² (σ is the Stefan—Boltzman constant). Therefore, the ratio $q_b/q_h \sim 10$. It defines the role of the radiation only for the case when the shock-compressed layer has an optical thickness of $\tau \gg 1$. Thus, the shock wave for these values of the velocity and density of the advancing jet with a quite large optical thickness of the gas behind the front is not only intensely radiating, but is also "supercritical" in the terminology of [7]. However, with a not too large thickness of the shock-compressed layer and gas density in it, the condition $\tau \gg 1$ is not satisfied.

Suppose that the characteristic length of the jet is ~10 cm and its mass (per unit area) is ~10^{-4} g/cm², i.e., the kinetic energy per unit area is ~10^2 J/cm². These parameters are characteristic for experiments [4, 5]. With the temperatures and densities of the gas behind the shock front stated above, the shock-compressed layer with a thickness of ~1 cm is optically transparent. This follows from Fig. 1, where the dependences of the degree of blackness η of a uniformly heated layer with thickness x = 1 cm on the temperature T are shown. The values of the logarithms of the relative densities log (ρ/ρ_L) are shown on the corresponding curves. The solid curves give the values of η obtained by taking into account only continuous absorption, while the dashed curves give the values obtained by taking account of the lines. It can be seen that in the range of variation of the parameters of the problem being considered, the blackness coefficient η ~ 0.03. Thus, the radiation flux density $q_r = \eta\sigma T^4 \sim 30$ MW/cm², i.e., $q_r/q_h \sim 0.3$, and the role of radiation, as before, is large. With a reduction of the initial density ρ of the jet by an order of magnitude, η decreases to approximately 10^{-3} and, despite the ratio of q_b/q_h increasing to 10^2, the ratio q_r/q_h decreases to 0.1. With increase of the density by an order of magnitude (up to 10^{-4} ahead of the front and up to 10^{-3} g/cm³ behind it), the degree of blackness increases up to values which are close to unity. At the same time, the ratio q_b/q_h falls to 1. Consequently, we have $q_r/q_h \sim 1$.

With further increase of density, the relative role of radiation should decrease because of the decrease of q_b/q_h. Moreover, the effect of screening of the radiation emerging from the shock front must appear.

A significant part of the radiation emitted by the front belongs to the ultraviolet range and can be absorbed by a relatively cold impinging gas. Therefore, ahead of the shock front a so-called heated layer is formed [7]. With $q_r/q_h \sim 1$, the temperature ahead of the front should be on the order of the temperature behind it. However, in the case of a relatively small gas density ρ or a small jet length L, when the mass m of the layer is small, the effect of screening may be small. In fact, when $\rho \sim 10^{-4}$ g/cm³ and the temperature in the

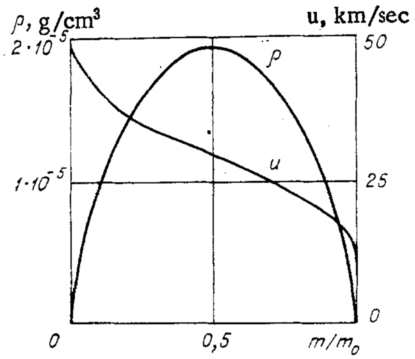

Fig. 2

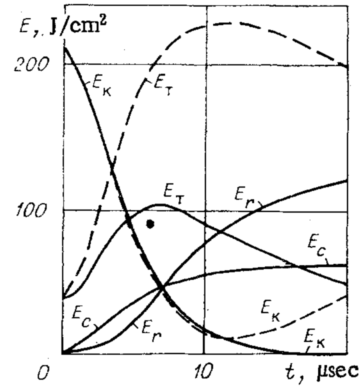

Fig. 3

heated layer T ~ 4-5 eV, the mass absorption coefficient $\varkappa$ of radiation with quantum energies of $\varepsilon \approx$ 25-70 eV amounts on the average to 10^3 cm²/g. With a temperature of 7-10 eV, it is reduced to approximately 10^2 cm²/g. Therefore, even with a comparatively small heating up of the gas ahead of the front of mass of the order of 10^{-3} g/cm², it is found to be transparent for the emitted radiation. With a density of 10^{-5} g/cm³, when the impinging layer of gas has a mass of order 10^{-4} g/cm², it is found to be almost transparent for these quanta, even in the cold state. Consequently, the overwhelming part of the emitted radiation can go out "to infinity." The weakness of the screening effect and the possible transparency of the gas behind the front with limited mass of the impinging gas distinguishes, in principle, this problem from the problem (considered in detail in [7]) concerning the motion of an intensely radiating shock wave through a boundless medium when the gas behind the front is nontransparent but the screening effect is large.

Thus, the estimates show that with gas densities on the order of 10^{-4} to 10^{-5} g/cm³ and with a thickness of the layer of advancing gas of order 10 cm, the radiation energy emitted in vacuo may be of the same order of magnitude as the kinetic energy of the jet. With reduction of density or with its increase by comparison with the values given, the relative fraction of radiation can be reduced. In the latter case, emission will occur mainly only during exit of the shock wave at the boundary of the advancing layer with the vacuum and at the stage of subsequent dispersion. In the greater part of the period of propagation of the shock wave through the gas, it will be screened.

It follows from what has been said that by changing the density of the impinging gas, the coefficient of transformation of the kinetic energy of the jet E_k into thermal radiation E_r can be changed. Naturally, the position of the maximum of the coefficient of transformation E_r/E_k with respect to the density varies with the velocity of the jet and its length. With increase of the length of the jet (with constant density), the opacity and, consequently, also the maximum of E_r/E_k with respect to density are established for low gas densities. With increase of velocity, the temperature of the gas behind the shock front and the transparency of the shock-compressed layer are increased, and therefore the maximum of E_r/E_k with respect to density should be observed at high gas densities or (and) at large jet lengths. In order to verify the validity of the pattern of the radiation-gasdynamic processes described above and the estimates made of the principal parameters, we shall consider some results of the numerical calculations of the problem concerning the impact against a plane obstacle of a plane layer of aluminum vapor, moving with a high velocity.

Owing to the action of the resulting radiation on the obstacle, it will be vaporized. It has been assumed, for simplicity, that the material of the obstacle is also aluminum. In the calculations, the initial values of the velocity of motion, the gas density, the mass of the layer, and its length were varied. The initial velocity distribution was assumed to be a linear function of the distance, which is characteristic for the inertial stage of motion of the gas jet in vacuo, when its thermal energy is significantly less than its kinetic energy. The maximum temperature of the gas in the jet before impact was 1 to 2 eV, which occurs, for example, under the conditions of certain of the experiments [4, 5]. The initial gas density distribution along the length of the jet corresponded approximately to these same experiments and was a symmetrical function (close to sinusoidal) relative to the middle of the layer. Figure 2 shows the initial velocity and density distributions with respect to the dimensionless mass of the layer m/m_0 (m_0 is the total mass) in one of the versions of the calculation, which we shall arbitrarily call the primary version. Similar distributions for

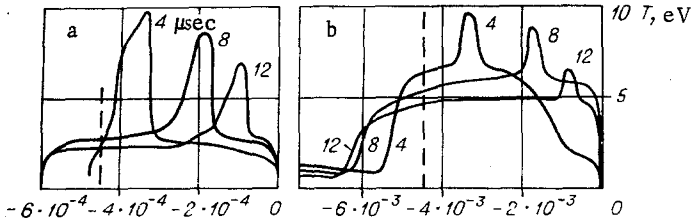

Fig. 4

other versions are obtained by means of a similar extension of compression along both axes. In the given case, the maximum velocity amounted to 49 km/sec, the total kinetic energy E_k = 212 J/cm², the internal energy E_T = 38 J/cm², the total mass $m_0 = 4.5 \cdot 10^{-4}$ g/cm², the maximum density $1.9 \cdot 10^{-5}$ g/cm³, and the average density $1.15 \cdot 10^{-5}$ g/cm³. The density decreases in proportion to the motion of the "free" jet, due to its stretching. In the "control" Euler section, where the head of the jet was located at the initial instant (and where the obstacle subsequently was placed), with free motion of the jet in vacuo at the time 4.5 μsec the density should reach a maximum value of $1.2 \cdot 10^{-5}$ g/cm³, and the velocity should amount to 34 km/sec. The calculation of the vaporization of the obstacle was carried out by using the vaporization wave representation [8, 9]. The heat transfer in the depths of the condensed substance was taken into consideration by means of the normal thermal conductivity. The gas-dynamic part of the program was close to that used in [8, 9] during the investigation of the action on an obstacle of monochromatic radiation or in [10] for the analysis of the action of the emission of a continuous spectrum. When calculating the radiation transfer, averaging was carried out with respect to frequencies within the limits of eight groups, the boundaries of which were as follows: 0...2, 0...6, 0...12...18...25...39...68...153 eV. It follows from Fig. 1 that with densities, temperatures, and dimensions of the layer which are typical for the given problem, the role of the lines in radiation transfer is small. Therefore, for simplicity, the lines will not be taken into consideration.

Figure 3 shows the time variation of the quantities E_k, E_T, E_r, and also E_c — the thermal energy in the condensed phase. The instant t = 0 corresponds to the start of collision of the jet with the obstacle. The solid line shows the relationship in a calculation in which radiation is taken into account, while the dashed line is for the same calculation without taking radiation into account. It can be seen that the kinetic energy varies in an almost identical manner; however, when radiative transfer is taken into consideration, a considerable part of it converts to radiation energy. Thus, at 15 μsec, when the shock wave withdraws from the obstacle by 6 cm, the losses to radiation into the vacuum amounts to ≈50% of the initial kinetic energy of the jet.

Figure 4 shows the temperature distributions T with respect to the bulk Lagrangian coordinate m. The times t are shown on the corresponding curves. Figure 4a refers to the primary version described above, and Fig. 4b refers to the version with the initial density (and mass) of the jet increased by a factor of 10 (with constant values of the other parameters). The dashed lines mark the boundary between the vapor of the jet and the obstacle. At the boundary with the vacuum, m = 0.

The temperature distribution in Fig. 4a corresponds to the case of strong luminescence bearing a spatial nature. Behind the shock front, the temperature decreases rapidly because of radiation both to the vacuum and to the obstacle. We note that in the same calculation, but without taking account of radiation, the temperature distribution over the mass of the shock-compressed layer was quite uniform.

Near the obstacle, a dense and relatively cold layer of erosion vapor is formed, the total mass of which may reach 50-70% of the mass of the impinging jet. The heated layer ahead of the shock front is weakly expressed. The nature of the temperature distribution in Fig. 4b, however, is close to the typical distribution in a wave with supercritical amplitude [7]. At the instant 8 μsec, the edge of the heated layer reaches the boundaries with the vacuum and the maximum radiation yield is observed.

Thus, when radiation effects are taken into account, greater energy losses by radiation are observed, the mass of vapor is increased significantly, and the nature of the distribution of the parameters changes; i.e., radiant transfer is the defining physical factor in the problem being considered.

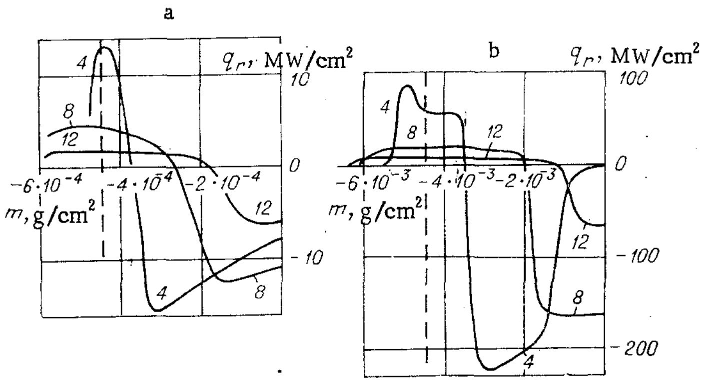

Fig. 5

Screening of the radiation emitted to the side of the vacuum is weak for the primary version, but for the second version (with 10-fold density) the shock front, in practice, is screened for a long time. This can be seen from Fig. 5, where the distributions of the radiation flux density q_r with respect to the mass m are given at the same instant as in Fig. 4. In the primary version, the maximum radiation flux density going out into the vacuum reaches 12 MW/cm² at 7 μsec and is significantly lower than the radiation flux density of an absolutely black body, with maximum temperatures behind the shock front at these instants. The corresponding effective temperature amounts to only 3.3 eV and is far less than the true temperatures in the plasma. It is of the same order as the values of the brightness temperatures in the experiments of [4, 5]. With an increase of the initial density by a factor of 10, the maximum radiation flux density into the vacuum increases to 200 MW/cm² and the effective temperature is ≈6.7 eV (close to the true temperature). Thus, an increase of density of the jet gases contributes to a significant increase of the brightness temperature.

The spectra of φ_ε^0 of the outgoing radiation into the vacuum at the initial instant t = 7 μsec are represented in Fig. 6. Curve 1 corresponds to the primary version and curve 2 corresponds to the version with a 10-fold initial density. In the first case, the spectrum is quite remote from a Planck spectrum, but in the second case it is close to it and harder.

Despite the strong change of density of the jet over the range of its values considered, the ratio of the energy E_r radiated into the vacuum to the initial kinetic energy of the jet E_k^0 varies with time, starting from 7-8 μsec, in an almost identical way. This is because the process of deexcitation takes place so rapidly that the intensity of the radiation (in the absence of screening) is limited, in essence, only by the stopping process of the jet and the speed of "response" of the kinetic energy. Therefore, the magnitude of the radiation pulse is almost proportional to the kinetic energy, and the maximum radiation flux density is proportional to the hydrodynamic flux density. When the density is reduced by a factor of 10 in comparison with the primary version, the relative fluorescence at 15 μsec is decreased from 50 to 30%. The dependence of the quantity E_r/E_k^0 on t/t_* varies relatively weakly and with a change of the maximum velocity of the jet within the limits 30-70 km/sec for an initial density of the first version ($E_r/E_k^0 \approx$ 50-60% with $t/t_* \approx$ 3 to 4; t_* is the characteristic time of impract, inversely proportional to the velocity of the jet). Figure 7 shows the variation of E_r/E_k^0 with t for a version having the density and mass of the primary version (curve 1), but with a velocity of 65 km/sec, and also for versions having the density (and mass) increased by a factor of 3 to 10 (curves 2 and 3, respectively). It can be seen that in this case the magnitude of the fluorescence is found to be stable for change of density, and the greatest fluorescence is observed for an intermediate value of the maximum initial density — $6\cdot10^{-5}$ g/cm³, which was also predicted by the estimates given above.

Thus, the estimates and the calculation show that, based on the impact of the gas jet against the obstacle, extremely intense radiation sources in the visible and ultraviolet regions, in the region of the far vacuum ultraviolet and, in the long term (with increase of the jet velocity), also in the ultrasoft x-ray region, canbe created; and the radiation energy can be on the order of the kinetic energy of the jet, while the pulse duration is of the order of the duration of the impact.

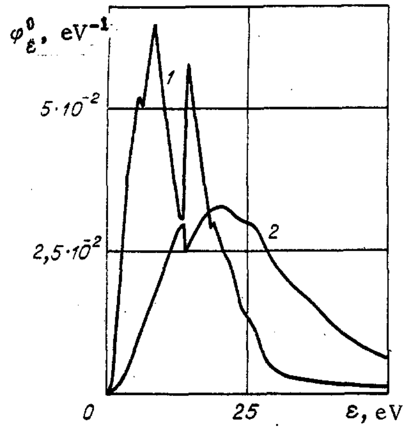

Fig. 6

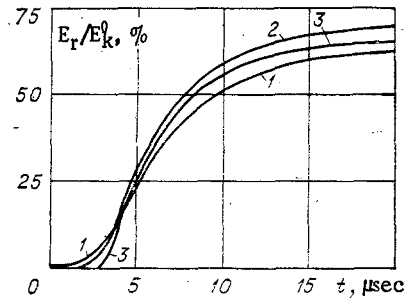

Fig. 7

The authors thank Yu. S. Protasov and A. S. Kamrukov for valuable discussions during the formulation and carrying out of this work, and V. P. Buzdin and I. B. Kosarev for providing the tables of spectral absorption coefficients of aluminum, taking account of line absorption.

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