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SUPERSONIC RADIATION WAVES WITH MOTION OF PLASMA

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A numerical solution is obtained to the two-dimensional radiation-gasdynamics problem of plasma formation under laser action.

Laser radiation acting on a target produces absorption waves which travel in the opposite direction to the laser beam. The leading role in the wave propagation process can be played here by any of the various mechanisms, heat conduction (slow luminous combustion), hydrodynamics (luminous detonation), or spontaneous thermal radiation of plasma (subsonic and supersonic radiation waves), depending on the density and the composition of the gaseous medium as well as on the flux density and the wavelength of laser radiation and on the duration of the laser pulse [1]. In supersonic radiation waves [1-3] the plasma, especially near their fronts, remains almost stationary and its density remains near its initial level. Such a pattern has been confirmed by one-dimensional calculations [2] as well as by experiments [3, 4]. This agreement between theory and experiment was subsequently utilized as the basis for calculating two-dimensional supersonic radiation waves [5]. Assuming a constant plasma density made it possible to treat the equations of radiation transfer simultaneously with only one energy equation, without the need to resort to the complete system of equations of gasdynamics.

The role of gasdynamic processes is not always minor, however, even when the propagation of wave fronts is effected by the radiation mechanism. The plasma can move intensely far away from the fronts of radiation waves. Furthermore, as the radiation flux density gradually decreases and transition to luminous detonation occurs, the role of plasma motion becomes increasingly significant. Accordingly, the method of calculations in [5] was extended to the complete system of equations of radiation gasdynamics in the axisymmetric formulation

$$\frac{\partial \rho}{\partial t} + \operatorname{div}(\rho \vec{v}) = 0, \quad (1)$$

$$\frac{\partial \rho u}{\partial t} + \operatorname{div}(\rho u \vec{v}) + \frac{\partial p}{\partial z} = 0, \quad (2)$$

$$\frac{\partial \rho w}{\partial t} + \operatorname{div}(\rho w \vec{v}) + \frac{\partial p}{\partial r} = 0, \quad (3)$$

$$\frac{\partial \rho e}{\partial t} + \operatorname{div}(\rho e \vec{v} + p\vec{v} + \vec{q}) = 0, \quad (4)$$

$$\frac{\partial I_\nu}{\partial s} = -k_\nu (I_\nu - B_\nu),\ \vec{q} = \int_{4\pi}\int_0^\infty I_\nu d\nu \vec{\Omega} d\Omega, \quad (5)$$

$$e = e(T, \rho),\ p = p(T, \rho). \quad (6)$$

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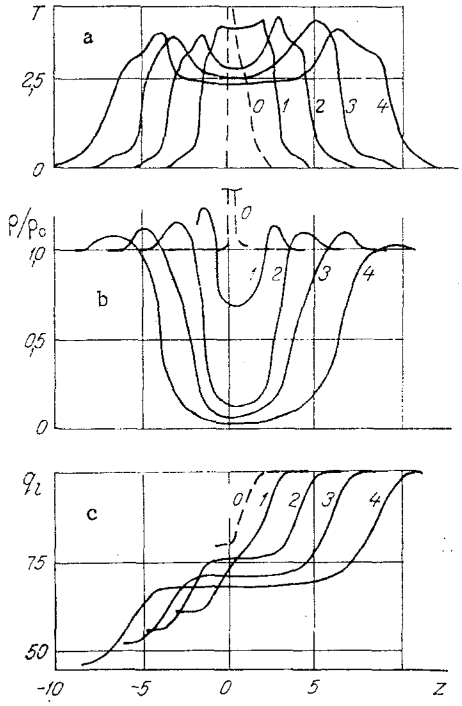

Fig. 1. Distribution of (a) temperature T (eV), (b) relative density ρ/ρ_0, (c) flux density of laser radiation q_l (MW/cm^2) along the axis of symmetry.

Here ρ is the density; e, internal energy per unit mass; u and w, respectively, the axial component and the radial component of the velocity vector $\vec{v}$; I_ν, the intensity of radiation at frequency ν propagating along the laser beam in a direction characterizable by the unit vector $\vec{\Omega}$; s, the distance along this beam, k_ν, the spectral absorption coefficient; B_ν, the Planck function; and q, the density of radiant energy flux.

The complete system of Eqs. (1)-(6) was solved through splitting it into the radiation part and the gasdynamic part, Eq. (5) being solved with the distributions of temperature and flux density known at some instant of time, then the radiation flux $\vec{q}$ being determined, and the system of Eqs. (1)-(4) of gasdynamics being solved with the radiation flux known.

The scheme of [5] was used for solving the radiation part of the problem. No simplifying assumptions were made beforehand concerning the spectrum characteristics and the radiation pattern. There were no formal constraints in that scheme on the number of spectral intervals and the number of rays. The combination of angles and frequency intervals was selected through a reasonable tradeoff between accuracy requirements and capabilities of modern computers (making, accordingly, the radiation intensity a function of six variables). In the calculations shown here the transfer equation was solved for 50 rays at each point and for six spectral groups with coefficients in each determined through averaging of values given in tables of spectral absorption coefficients for each group. The number of spectral intervals and their limits were established on the basis of repetitive solution of the transfer equation for several rays in various directions and within various frequency intervals, then comparing the obtained radiation fluxes with those obtained from solutions for the maximum number of frequency intervals (650 values in tables of spectral absorption coefficients [6]).

In the gasdynamic part of the program we used the scheme of [7], constructed for an Euler grid just as the scheme in [5]. That scheme is a conservative one, with weak dissipative properties.

Calculations were made for the problem of expansion of a plasma cluster in air from an initial relative density $\delta = 0.01$, expansion caused by radiation from a neodymium laser with constant (in time) radiation flux density $q_0 = 100$ MW/cm^2. The radius of the light spot r_0 was varied from 1.5 to 3 cm.

The two-dimensional calculation was started by stipulating a cylindrical layer of plasma with distributed parameters (temperature, density, and velocity) along the z axis, these

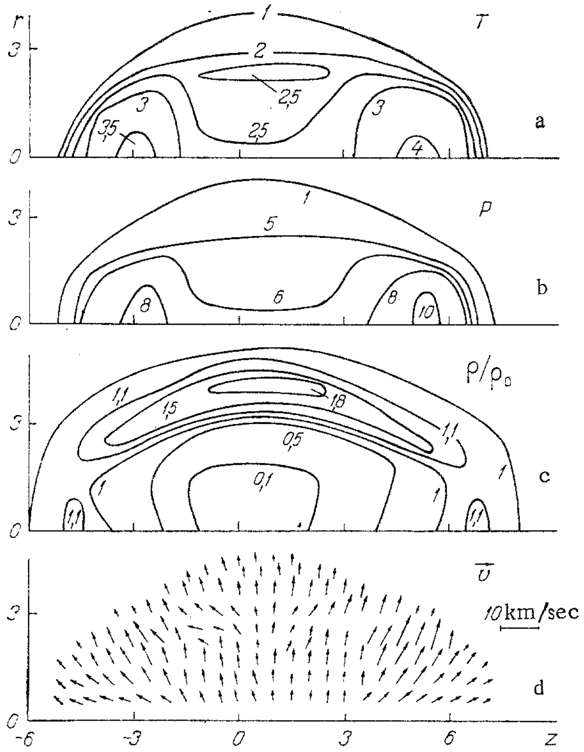

Fig. 2. Isotherms (a), isobars (b), isochores (c), and velocity field (d) in plane passing through axis of symmetry.

parameters having been obtained by one-dimensional calculation for the analogous variant (but with a thin evaporating aluminum barrier included) at the instant of time the thickness of the plasma layer would become 2.5 cm, i.e., comparable with the radius of the light spot. The presence of this barrier was disregarded in the two-dimensional calculation. The starting data thus corresponded to complete combustion of the plasma-initiating aluminum foil. The transverse initial dimensions of the plasma were stipulated as being equal to the radius r_0 of the light spot.

The equation of state for air was set up according to tables [8]. The limits of the spectral groups were 0...3...6.52...10...18.6...75...248 eV. The maximum number of nodes in the difference grid was 800 (20 along the radius and 40 along the z axis). The initial space step was 0.25 cm along the z axis and 0.125 cm along the radius for $r_0 = 1.5$ cm and 0.25 cm for $r_0 = 3$ cm. The space step was doubled several times in the course of calculations, as the plasma region became wider.

The results for $r_0 = 1.5$ cm are shown in Figs. 1 and 2. The graphs in Fig. 1 depict the distributions of plasma parameters (T, ρ/ρ_0, q_l) along the z axis of symmetry at several instants of time. The numerals at the curves indicate the instants of time t (μsec). The front of a supersonic radiation wave propagates against the laser beam, but the values of parameters at the wave front in this case (maximum temperature at the wave front $T_f = 4$ eV, velocity of front propagation $D = 20$ km/sec) are much lower than in [5] ($T_f = 8$ eV, $D = 70$ km/sec) even though the ratio q_0/δ (on which the wave velocity and the temperature at the wave front depend) is the same.

It is to be noted that, in addition to the parameter q_0/δ, the ratio r_0/l plays just as significant a role in propagation of a radiation wave.

Indeed, the characteristic width Δ of the wave front (if one is formed at all) cannot exceed the transverse dimensions of the plasma (which are of the same order of magnitude as the diameter of the light spot) and at the same time the length of the laser radiation path. While in [5] ($l \gtrsim 0.1$ cm, $r_0 = 0.4$ cm, $l < 2r_0$) the width of the front was $\Delta \lesssim l$, i.e., almost the entire laser radiation flux was absorbed at the wave front, here the lowering of the initial density of the medium (by one order of magnitude) results in a much longer laser radiation path ($l \gtrsim 10$ cm) and in a width of the wave front $\Delta \lesssim 2r_0$ at a beam diameter $2r_0 < l$ so that only some fraction of the incident radiation flux, approximately equal to the ratio

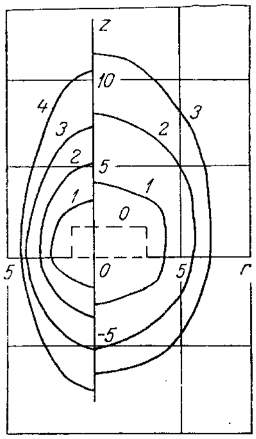

Fig. 3. Evolution in time of the plasma region.

$2r_0/l$, is absorbed at the wave front. This fraction is approximately 30% for r_0 = 1.5 cm and correspondingly larger, approximately 60%, for r_0 = 3 cm. These rough estimates of the amount of laser radiation flux absorbed at the wave front agree fairly well with the results of calculations (Fig. 1c). We are thus dealing here with propagation of supersonic radiation waves with incomplete absorption of the laser beam energy. In the course of lateral expansion of the plasma (across the laser beam) the characteristic width Δ of the front increases gradually and its optical thickness increases also, which results in a larger fraction of the laser radiation flux being absorbed at the wave front and in a correspondingly somewhat faster propagation of that wave front.

As a result of lateral expansion of the plasma jet, within its center part there forms a region of low density (Fig. 1b), almost one order of magnitude lower than that of the unperturbed gas, through which laser radiation passes being hardly absorbed at all and reaching the back edge of the plasma jet where it sustains propagation of the latter along the laser beam at a velocity close to that of the front edge.

The graphs in Fig. 2 depict isotherms (Fig. 2a), isobars (Fig. 2b), and isochores (Fig. 2c) at time t = 3 μsec in a plane passing through the axis of symmetry; the actual temperatures T, pressures P, and relative densities ρ/ρ_0 are indicated next to the corresponding curves. The diagram in Fig. 2d depicts the velocity field $\vec{v}$. The velocities of dispersing plasma ($v \lesssim$ 10 km/sec) are much lower than the velocities of its front propagation, but the effects of hydrodynamic motion appear quite strongly nevertheless. Because the lateral expansion of the plasma jet is appreciable, relative to the radius r_0 of the laser beam, the density decreases also appreciably and the center of the plasma region brightens up with attendant decrease of temperature (Fig. 2a) and pressure (Fig. 2b) behind the wave front.

The diagram in Fig. 3 depicts the evolution of the plasma region, the curves here corresponding to the location of its boundary at temperature T = 1 eV as a function of time (instants of time in μsec are indicated next to the curves), for r_0 = 1.5 cm to the left of the z axis and for r_0 = 3 cm to the right of the z axis. As the radius of the laser beam decreases from 3 to 1.5 cm, the rate of plasma jet expansion decreases (to almost one half) in all directions. Further decrease of r_0 can cause the propagation of supersonic radiation waves to cease.

NOTATION

t, time, μsec; r, z, cylindrical coordinates, cm; T, temperature, eV; p, pressure, bars; ρ/ρ_0, relative density inside the plasma region; q_l, flux density of laser radiation inside the plasma region, MW/cm^2; v, velocity, km/sec; δ, initial relative density of air; q_0, initial flux density of laser radiation, MW/cm^2; r_0, radius of the laser beam, cm; l, length of the laser radiation path, cm.

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HEATING AND BREAKDOWN OF PROTECTIVE LAYER AT PLASMA RETAINING WALL

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Expressions are derived for estimating the parameters of the boundary layer of cold plasma forming through the action of radiation on the thermal protection in a pulse-type reactor with wall retention of thermonuclear plasma.

In designs of pulse-type thermonuclear reactors with wall retention of the plasma [1] it has been proposed that the first wall of the chamber in direct contact with the thermonuclear plasma be protected by means of a renewable thin layer of liquid metal (e.g., lithium). Meanwhile, processes in a hot plasma are usually analyzed without taking into account the effect of such a protective layer and assuming, for instance, a constant temperature of the wall surface [2, 3]. The magnitude of the effect of such a layer depends, obviously, on the number and the characteristics of products of breakdown of this thermal protection which will make contact with the hot plasma. Inclusion of the equations of the protective layer in the overall scheme of numerical analysis greatly complicates the model of the process and limits the capabilities of the calculation process. In the first approximation, however, the behavior of such a layer can be described quite simply on the basis of the following considerations.

When a hot plasma is retained by a wall, then during the fusion reaction ($t_r \sim 1$–10 msec) the protective layer is exposed to radiation and the pressure in the chamber is usually supercritical for the layer metal ($p = 1$–10 kbar, $p_{cr} = 0.69$ kbar and $T_{cr} = 3223$°K [4]). Therefore, while absorbing the radiation energy, the metal passes continuously from liquid to plasmatic state without a discernable phase transition. During that time the thermal conductivity, which determines the rate of energy transfer through the layer, varies in an intricate manner (Fig. 1). Experimental data are available for the condensed state far from critical [4]. As the temperature rises and thus the density decreases, metals are found to lose their n-type conductivity [5] so that the thermal conductivity should decrease sharply down to levels characteristic of dielectrics. During transition to the plasmatic state, finally, the main role in energy transfer is played by radiative thermal conductivity.

The described trend of the temperature dependence of thermal conductivity of a metal suggests that the model of a thermal wave [6] propagating depthwise in the layer may be applicable here. The temperature is almost uniform behind the wave front, owing to the strong temperature dependence of radiative thermal conductivity. At the wave front the temperature drops sharply from the plasma level to $T_* \sim 2000$–3000°K, at which the thermal conductivity of liquid metal becomes appreciable. Ahead of the wave front there propagates a heating "spike" produced as a result of this higher thermal conductivity.

The temperature dependence of energy, density, and thermal conductivity at constant pressure in the plasmatic state can be approximated with power laws:

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