RADIATION CHARACTERISTICS OF PLASMA FLAMES FORMED BY ELECTRON-BEAM ACTION ON A TARGET

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A method is described for numerical study of the radiation properties of plasma flames produced by electron beam action. Calculation results are presented.

1. Intensive energy liberation caused by action of an impulsive high current electron beam on metals produces a crater in the target, with the erosion vapors being ionized and forming a plasma flame with a high temperature. Experiments have shown [1] that the flame temperatures may reach decades of eV, with densities of 0.01 g/cm^3, and vapor velocities of decades of km/sec. With such parameter values the plasma can obviously be optically opaque and experimental determination of its extremal parameters using optical diagnostics is difficult. In such a situation a combination of numerical modeling of the interaction with experiment permits acquisition of detailed information on the process. Using the model described in [2, 3] the present study will investigate the effect of radiant energy transport in the vapor flame on its parameters and on crater formation during action of a high-current electron beam with electron energy of 0.3 MeV.

We will consider the procedure used to calculate radiant losses in modeling the action of the beam on the target. Radiant energy transport can be calculated by the technique of [4], which considers the spectral composition of the radiation in the approximation of three groups, within which the absorption coefficients are assumed frequency-independent and equal to the Planck averaged spectral absorption coefficients [4, 5] (Fig. 1). Radiation is described by the term div F in the energy equation of the complete hydrodynamic system of equations. To obtain a finite difference expression for this term we use a solution of the radiation transport equation along a ray in some direction [6]:

$$I_\nu(\tau) = \int_{\tau_0}^{\tau} \varkappa_\nu I_{\nu p} \exp\left(-\int_{\tau'}^{\tau} \varkappa_\nu d\tau''\right) d\tau' + I_{0\nu} \exp\left(-\int_{\tau''}^{\tau} \varkappa_\nu d\tau'\right), \tag{1}$$

$$I_{\nu p} = 2h\nu^3 c^{-1} (\exp(h\nu/kT) - 1)^{-1}.$$

The equilibrium unilateral integral flux is then

$$B_p = \int_0^\infty B_{\nu p} d\nu = \int_0^\infty \pi I_{\nu p} d\nu = \sigma T^4.$$

The subscript ν indicates the dependence of the parameters on quantum energy. The radiation at the point τ along the chosen direction consists of all quanta generated along this ray. The first term describes the contribution of intrinsic radiation, while the second describes the contribution from external sources, attenuated due to absorption on the path from the boundary of the region τ_0 to the point τ.

To consider the angular distribution of the radiation we use the two-flux approximation and introduce unilateral fluxes in the positive (n+) and negative (n−) directions of the coordinate axes. It is assumed that at each boundary of the cell the fluxes in the n-th interval of quantum energies consist of the difference between these unilateral fluxes and are normal to the face surfaces of the cells. Then

$$F^n_{i\pm 1/2,j} = (F^{n+} - F^{n-})_{i\pm 1/2,j}, \quad F^n_{i,j\pm 1/2} = (F^{n+} - F^{n-})_{i,j\pm 1/2}. \tag{2}$$

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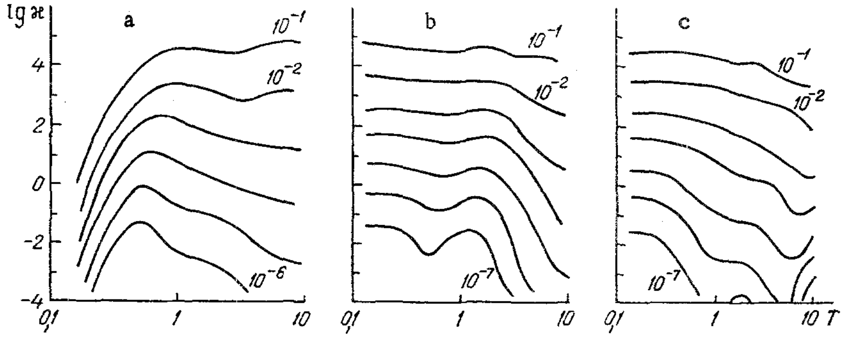

Fig. 1. Aluminum plasma absorption coefficients for three spectral groups: I) ε = 0.01-6.52 eV; II) 6.52-9.96 eV; III) 9.96-100. Digits on curves indicate ρ, g/cm³. T, eV; log κ, cm⁻¹.

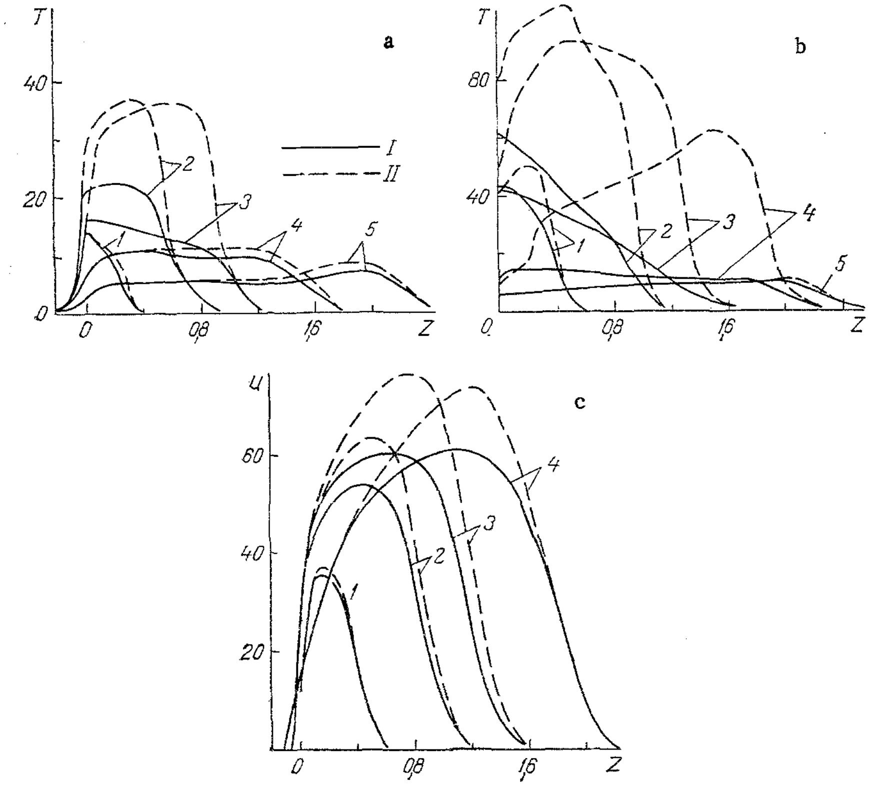

Fig. 2. Dynamics of plasma flame axial parameter distribution (I, calculation with radiation; II, without radiation): 1) 0.03 μsec; 2) 0.06; 3) 0.1; 4) 0.16; 5) 0.32; a, b) temperature profiles in variants 2 and 3; c) velocity profiles in variant 3. u, km/sec; Z, cm.

Using the solution of Eq. (1) for the radiant energy balance within each Eülerian cell and integrating over the quantum energy spectrum, we obtain an expression for the divergence of the integral radiant energy flux over the spectrum in the full system of equations. Multiplying the solution of Eq. (1) by π, for the unilateral fluxes along OZ and OR we have:

$$F^{n+}_{i+1/2,j} = q^n_{i,j} + F^{n+}_{i-1/2,j}\exp(-l^n_i),$$
$$F^{n-}_{i-1/2,j} = q^n_{i,j} + F^{n-}_{i+1/2,j}\exp(-l^n_i); \tag{3}$$

$$S_{j+1/2}F^{n+}_{i,j+1/2} = S_{j+1/2}q^n_{i,j} + S_{j-1/2}F^{n+}_{i,j-1/2}\exp(-l^n_j),$$
$$S_{j-1/2}F^{n-}_{i,j-1/2} = S_{j-1/2}q^n_{i,j} + S_{j+1/2}F^{n-}_{i,j+1/2}\exp(-l^n_j). \tag{4}$$

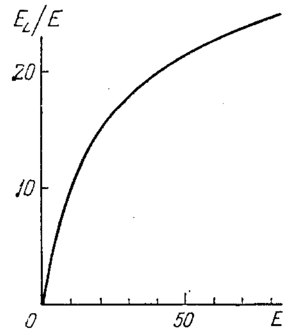

Fig. 3. Radiant energy loss from plasma flame vs energy absorbed by target. E, kJ; E_L/E, %.

Here the intrinsic radiation flux

$$q_{i,j}^n = \begin{cases} l_i^n B_{i,j}^n, & l_i^n < 1, \\ B_{i,j}^n, & l_i^n > 1. \end{cases} \tag{5}$$

In Eqs. (3)-(5), $l_i^n = \varkappa_{i,j}^n \Delta z_i$, $l_j^n = \varkappa_{i,j}^n \Delta r_j$ are the optical thickness of the Eulerian cell in the direction of the axes OZ and OR. Finally, from Eqs. (2)-(5) in a cylindrical coordinate system we obtain a difference expression for the flux divergence [4, 7]:

$$\begin{aligned}(\mathrm{div}\,\mathbf{F})_{i,j} &= \frac{F_{i+1/2,j} - F_{i-1/2,j}}{\Delta z_i} + \frac{r_{j+1/2}F_{i,j+1/2} - F_{i,j-1/2}r_{j-1/2}}{r_j \Delta r_j} = \\ &= \frac{2q_{i,j}}{\Delta z_i} - \frac{F_{i+1/2,j}^- + F_{i-1/2,j}^+}{\Delta z_i}\left(-\exp(-l_i) + 1\right) + \\ &+ \frac{r_{j+1/2} + r_{j-1/2}}{r_j \Delta r_j} q_{i,j} - \frac{r_{j+1/2}F_{i,j+1/2}^- + r_{j-1/2}F_{i,j-1/2}^+}{r_j \Delta r_j}\left(-\exp(-l_j)+1\right).\end{aligned}$$

At the initial moment the fluxes at the boundaries of the calculation region are taken equal to zero, and intrinsic radiation is absent. Thus, the method described permits evaluation of the character of radiation from the plasma flame in two directions and estimation of the effect of radiation processes on the parameters.

2. We will consider the role of radiant processes for the following calculation variants: 1, energy absorbed by target in interaction region E = 0.856 kJ; 2, 4.8; 3, 16.2; 4, 20.1; 5, 85.1 kJ. In all variants the beam electron energy will be 0.3 MeV, and the form of the current pulse will be $I = I_0 \sin(\pi t/t_0)$ [3], where t_0 = 100 nsec. Beam diameter is 0.1 cm.

Comparison of the calculations shown in Fig. 2 reveals that radiant energy transport and loss from the vapor flame have no significant effect on the size of the crater formed. At the same time the vapor temperature decreases by a factor of 2-3 times during the interaction process. After completion of the interaction, by the time $t = 3t_0$, in both cases a developed flame is formed with approximately the same temperature of 10 eV. Insensitivity of the crater dimensions to radiant energy transfer processes can be explained by the fact that these processes do not affect the quantity of energy which is retained in the target and controls the dynamics of crater formation. Thus, at the completion of current pulse action in the variants with and without consideration of radiation the target material retains 1.7 kJ (variant 2), 5.5 (3), 8 (4), and 23 kJ (5), while the remaining energy is contained in the vapor flame with removal of a mass of $(5\text{-}10)\cdot 10^{-3}$ g from the crater.

We will now consider processes of radiant energy loss from the flame. In variant 2 the radiant losses from the plasma flame comprise 5.5%; in variant 3, 13.7; 5, 25% of the absorbed beam energy (Fig. 3). The plasma flames are then optically opaque, and radiant losses are determined essentially by their hot surface in the soft x-ray range of the spectrum with photon energies greater than 10 eV (spectral group III). This is evident from the time behavior of power radiated from the flame shown in Fig. 4. The maximum radiant powers of $9\cdot 10^8$, $1.4\cdot 10^{10}$, and $2\cdot 10^{10}$ W for variants 2, 3, and 5 are achieved in the third spectral group.

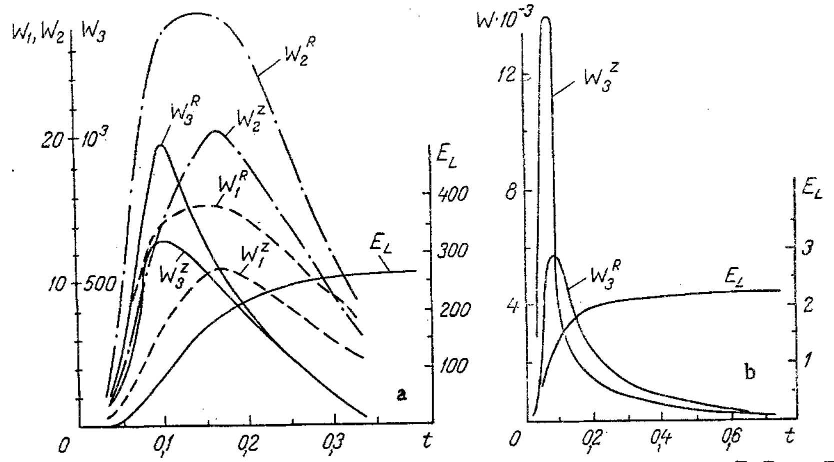

Fig. 4. Dynamics of plasma flame radiant losses ($W_1^{Z,R}$, $W_2^{Z,R}$, $W_3^{Z,R}$, radiant powers in direction of axes OZ and OR in spectral groups I, II, III; E_L, integral radiant energy loss): a) variant 2; b) 3. W, MW: t, μsec.

toward the end of current pulse action, and by the time $3t_0$ energy scintillation from the vapor flame is completed. We will note, finally, the large energy content of the plasma flame (10^2-10^3 kJ/g), which permits its use as a powerful radiation source, for example, in braking of the flame on an obstacle.

NOTATION

F, spectral integral of radiant flux; ν, quantum frequency; I_ν, spectral intensity of radiation along path τ; κ_ν, spectral absorption coefficient corrected for forced emission; (i, j), Eülerian cell number; n, spectral group number; $S_{j+1/2} = 2\pi r_{j+1/2}\Delta r_j$, Eulerian cell surface areas; Δz_i and Δr_j, dimensions of Eulerian cell among axes OZ and OR; t_0, current pulse duration; I_0, maximum beam current; T, temperature.

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