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HEAT FLUXES IN PLASMATRON CHANNEL

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Numerical simulation of a longitudinally blown electric arc by two-dimensional gas-dynamic equations made it possible to determine temperature and velocity fields, axial and radial components of convective, conductive and radiative heat fluxes, heat losses through a channel wall. The model takes into account radiation transfer in the actual spectrum of an electric-arc plasma. Using the results of calculations for argon and air, approximation expressions are obtained for the temperature dependences of the divergences of radiation fluxes.

At the present time, a number of industries incorporate technological processes based on the use of plasma devices and apparatuses. Thus, a growing number of uses are being found for electric-arc generators of plasma that allow one to obtain high-temperature gas flows for treatment and melting of metals, deposition of coatings, preparation of dispersed materials, as well as for scientific purposes. A special role in improvement of electric-arc generators is assigned to the study of the processes of energy exchange.

In an electric arc burning along the axis of a channel whose walls serve as the anode and in which gas is blown from the side of the cathode, it is possible to separate three regions: an expansion zone, a formation zone, and an asymptotic zone. Energetically most important are the first two zones, which compose the starting length of the arc. Taking into consideration the fact that the formation of temperature and velocity fields, as well as the strongest changes in the electric field intensity, pressure, and thermal characteristics occur over this length, the simulation of precisely this region is of particular interest. Using certain specific features of an electric arc burning in a linear plasmatron channel (the axial symmetry and laminarity of the flow, the presence of local thermal equilibrium, stationary state, absence of external magnetic fields, small effect of gravitational and self-magnetic fields) and separating the direction of a sharp change in the parameters (the parameters change much more rapidly radially than longitudinally), it is possible to describe the starting length of the arc by the Prandtl two-dimensional gas-dynamic equations (boundary layer approximation.) The possibility of their application for describing channel flows is widely discussed in the literature and it is shown that in calculations of actual engineering devices the relative values of the longitudinal velocity and pressure drop obtained by solving the Prandtl and Navier–Stokes equations coincide when $(x/d)\mathrm{Re}^{-1} > 0.02$, while in the vicinity of the inlet cross-section, when $(x/d)\mathrm{Re}^{-1} << 0.02$, they differ by only 2 and 3%, respectively.

Approximating the derivatives by finite differences on a six-point model, an implicit two-layer difference scheme was composed for the solution of which a data-flow variant of the sweep method was used. The method is most convenient for calculating the electric-arc characteristics in view of sharp changes of transfer coefficients over the channel radius (by several orders of magnitude). The algorithm of the problem solution makes provision for internal (with respect to nonlinearity), intermediate (for relationship between the equations), and external (for refinement of the pressure prescribed at the initial cross-section) iterations.

The two-dimensional model of a longitudinally blown electric arc in a local thermal equilibrium approximation made it possible to determine the following characteristics: the distributions of the temperature and velocity over the channel, the specific mass flow rate of the gas, the electric field intensity, the axial and radial components of convective, conductive, and radiative heat fluxes, heat losses through the channel wall, the mean-mass enthalpy, the specific radiation power at each calculated point. The calculations were carried out at atmos-

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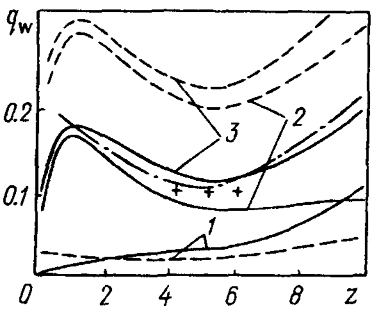

Fig. 1. Heat fluxes through channel wall (air: $I = 200$ A, $G = 2$ g/sec, $R = 1$ cm): 1) conductive; 2) radiative; 3) total; solid lines refer to the MPCh; dashed lines indicate allowance for radiation in volumetric approximation; dashed-dotted lines denote ∇q by formula (1); points denote experiment [2]. q_w, kW/cm^2, z, cm.

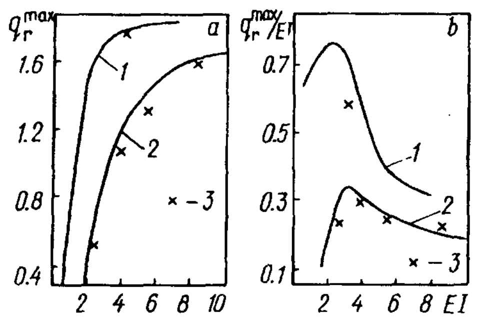

Fig. 2. The maximum radial radiation fluxes: a) radiation of unit length of arc column; b) relative radiation; 1) argon; 2) air; 3) experiment [2]. EI, kW/cm.

pheric pressure in an air flow for currents $I = 50-500$ A, gas flow rates $G = (1-5) \cdot 10^{-3}$ kg/sec, channel radii of 0.5 and 1 cm and in an argon flow for currents 10–200 A and $G = (0.5-3) \cdot 10^{-3}$ kg/sec.

Radiation transfer was taken into account by the method of partial characteristics (MPCh) [1]. Its main advantage is the possibility of integration over an actual spectrum, i.e., one which has not been subjected to schematization or simplification, before solving the gas-dynamic part of the problem. Among the merits of the MPCh are also the possibility of integration over the volume with the difference grid step of a gas-dynamic problem and high accuracy in determining the radiation flux and its divergence in view of the asymptotic nature of the method. Each variant of the problem was solved in two stages. At the first stage radiation was taken into account in an approximation of volumetric de-excitation, at the second stage the radiation transfer in the actual spectrum was considered. This made it possible to reveal the effect of radiation reabsorption on the calculated characteristics of the arc and to obtain their quantitative agreement with experimental data. This effect was most noticeable on temperature fields, heat fluxes, and mean-mass enthalpies. Allowance for radiation transfer in the actual spectrum decreases the axial plasma temperature over the stationary section by 500–2000 K, depending on the variant of calculation, whereas at the wall it increases the plasma temperature by 1000–2000 K. This is accompanied by a 50% decrease in heat losses through the channel wall (Fig. 1). The minimum on the distribution of $q(z)$ corresponds to the termination of arc expansion, and by its position we can determine the expansion zone length l_{exp}, since l_{exp}, by its very definition, is usually that cross-section in which conductive flow through the wall begins to grow. Over the starting length the radiative flux into the channel wall is smaller for an air arc than for an argon one at the same discharge power (Fig. 2a). As the power increases up to 2 kW/cm in argon and up to 4 kW/cm in air, the radiation of a unit length of the arc column increases sharply. At higher powers the fraction of radiation in the energy balance of the arc decreases (Fig. 2b).

Using radial distributions of the temperature and divergence of radiation flux, dependences of the specific radiation power on temperature were constructed for each variant of computation. In the investigated ranges of the determining parameters the temperature fields change insignificantly from variant to variant, and all the $\nabla q(T)$ curves fall into the shaded region (Fig. 3). In spite of some scattering, the data of all the variants of computation can be described by one "generalized" curve, which differs from the similar dependence in the volumetric de-exitation approximation by the presence of negative values at temperatures of 1000–10,000 K and by a greater radiation flux divergence at high temperatures. Using the least-squares method, the "generalized" dependences $\nabla q(\theta)$ were approximated by the expressions

$$\nabla q(\theta) = -1.676 + 1.194\theta - 0.356\theta^2 + 0.128 \cdot 10^{-1}\theta^3 +$$

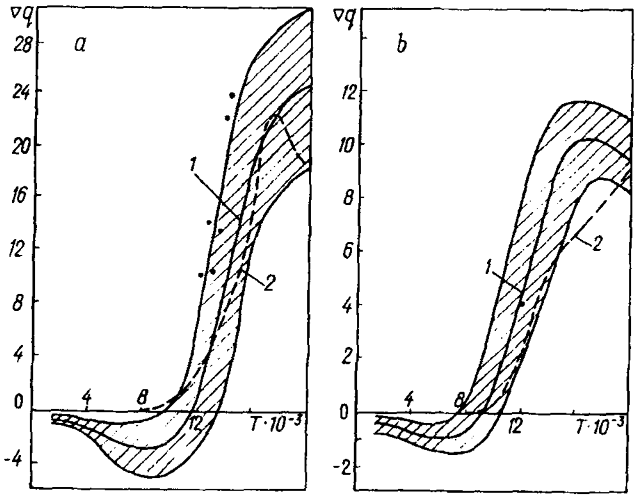

Fig. 3. Divergence of radiation flux of air (a) and argon (b) versus temperature ($P = 0.1$ MPa): 1) in an actual spectrum; 2) in volumetric deexcitation approximation according to [3] (a) and to [4] (b); the points denote the experiment according to [2] (a) and to [5] (b). ∇q, kW/cm^3, T, K.

$$+ 0.237\cdot 10^{-2}\theta^4 - 0.155\cdot 10^{-3}\theta^5 + 0.250\cdot 10^{-5}\theta^6, \quad \theta = T/10^3 \tag{1}$$

for air and by

$$\nabla q\,(\theta) = 10.285 \ln\theta + 29.913 - 75.882\theta + 63.105\theta^2 - 16.038\theta^3, \quad \theta = T/10^4 \tag{2}$$

for argon. The use of relations (1) and (2) for determining the characteristics of an electric arc reduces the computer time for each variant to 15 min, i.e., by almost an order of magnitude. To prove the possibility of applying these expressions, we performed calculations of several variants of the problem with "generalized" divergences of radiation fluxes. For comparison, Fig. 1 illustrates the heat flux into the channel wall as calculated using expression (1). In this case the accuracy of calculations could be impaired in certain variants by 10–15%. This means that the use of expressions (1) and (2), which account for radiation transfer in the actual spectrum, saves machine time without a significant loss of accuracy. In any case, these relations are quite suitable for engineering calculations. But, to be sure, they must be used in those ranges of determining parameters that have already been investigated.

NOTATION

z, axial coordinate; d, channel diameter; R, channel radius; Re, Reynolds number; I, current strength; G, flow rate of gas; P, pressure; T, temperature; q, heat flux; ∇q, radiation flux divergence. Subscripts: w, wall; r, radiative; max, maximum.

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