AN INVESTIGATION OF THE EFFECT OF PLASMA ROTATION ON THE CHARACTERISTICS OF A POWERFUL ELECTRIC ARC

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UDC 537.52

The study of a rotating plasma is important for the solution of a number of applied problems of plasma physics and plasmochemistry [1]. A generator of low-temperature plasma combined with a chemical reactor, i.e., a plasmochemical reactor, is a basic unit of the new chemical technology. In large- and medium-tonnage chemical processes a number of serious requirements are imposed on them, one of which is high power of the plasmochemical reactor. As the plasma density and temperature increase, the volume radiation losses play a dominant role in the total power balance of the arc. The electric discharge is subject to the superheating instability [2-5], which can become an obstacle on the path to increasing the plasmotron power.

Twisted fluxes of plasma-forming gas have found widespread application for spatial stabilization of the arc on the vortex axis. The possibility of creating high-efficiency electric arc heaters based on the use of stabilization of the arc in the vortex chamber, which is characterized by a large ratio of the circumferential velocity to the average flow rate of $v_\varphi/u = 100$, has been shown in [6]. Spatial stabilization of the arc by a vortex in the plasmotron channel provides for stability of the output parameters of the gas and prevents intense disintegration of the electrodes.

The effect of plasma rotation on the power and electrical characteristics of an argon arc is numerically investigated in this paper with self-compression of the arc filament by the intrinsic magnetic field of the axial current taken into account.

A steady arc filament which is symmetric with respect to the azimuth φ and uniform along the z axis burning in a laminar twisted flow of a plasma-forming gas is discussed. All the quantities characterizing the arc depend only on radius r. The field intensity E is directed along the axis, and since the electric field is irrotational, it is constant over the cross section of the discharge. A rotating axisymmetric electric arc is described by the following system of MHD equations, which includes the momentum and energy conservation equations, Maxwell's equation, and Ohm's law [7]:

$$\frac{dP}{dr} = -jH + \frac{\rho v_\varphi^2}{r}; \tag{1}$$

$$\frac{1}{r}\frac{d}{dr}\left[r\varkappa(T, P)\frac{dT}{dr}\right] = \varepsilon(T, P) - \sigma(T, P)E^2; \tag{2}$$

$$\frac{1}{r}\frac{d}{dr}(rH) = \mu_0 j; \tag{3}$$

$$j = \sigma(T, P)E, \tag{4}$$

where T is the temperature, P is the gas kinetic pressure, H is the magnetic field induction, j is the current density, c is the speed of light, ρ is the density, v_φ is the azimuthal rotational velocity, $\varkappa$ and σ are the thermal conductivity and electric conductivity coefficients of the plasma, ε is the integrated emittance of unit volume of the plasma, and μ_0 is the magnetic permeability of a vacuum.

The values of the transport coefficients of an argon plasma were specified in the calculations in the form of tables based on the data of [8]. Their dependence both on temperature and on pressure has been taken into account. In view of the smallness of the

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Novosibirsk. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 4, pp. 7-12, July-August, 1981. Original article submitted May 24, 1980.

0021-8944/81/2204-0443$07.50

magnetization parameter $\omega_e\tau_e \ll 1$, one can neglect the effect of the azimuthal magnetic field on the transport coefficients. The emission power (W/cm³) was calculated by the procedure proposed in [9]:

$$\varepsilon = 5.6\cdot 10^{-26}\pi \left(\frac{T}{10^4}\right)^{1/2} e^{-\frac{\Delta I}{kT}} N_e \left[N_+ \exp(h\nu_g/kT) + Z_i^2 N_{++} \exp\left(h\nu_g^+/kT\right)\right], \tag{5}$$

where ν_g and ν_g^+ are the limiting frequency of a neutral atom and an ion, ΔI is the decrease of the ionization potential, k is Boltzmann's constant, Z_i is the multiplicity of ionization, and N_+ and N_{++} are the concentrations of singly and doubly ionized argon. The plasma is assumed to be optically thin, and reabsorption of radiation is not taken into account.

The following law of the radial distribution of the circumferential velocity was specified for the gas dynamical method of twisting of the gas in the vortex chamber:

$$v_\varphi = (D/r)(1 - \exp(-Kr^2)), \tag{6}$$

from which it follows that the core rotates according to the rigid-body law, and the periphery rotates according to the potential law. The constants D and K are related as follows to the maximum velocity v_m and its coordinate r_m:

$$D = 1.4 r_m v_m, \quad K = 1.25/r_m^2.$$

We note that Eq. (6) agrees well with the experimentally measured radial distribution of v_φ in a twisted plasma jet [10].

One can also accomplish rotation of the plasma with a rotating electromagnetic field [11]. The plasma is contained by the channel walls, and its tangential velocity is equal to zero on them. The viscosity

$$v_\varphi = \frac{RJ_{0z}}{c^2(\eta_i + \eta_a)}\, x(1 - x^2), \tag{7}$$

where R is the channel radius, J_{0z} is the amplitude of the high-frequency current, $x = r/R$, and η_i and η_a are the viscosity of ions and atoms, plays an important role in the establishment of the radial distribution of the azimuthal velocity [11]. We note that if one expands the exponent in Eq. (6) in powers of r and discards terms of less than the fourth power of r, then we obtain an expression for the azimuthal velocity which agrees with Eq. (7).

A two-point boundary-value problem is being solved. It is necessary to supplement the system of quasilinear Eqs. (1)-(4) with the following boundary conditions, which completely determine the solution:

$$\begin{gathered} \text{at} \quad r = 0 \;\; P = P_0,\; T = T_0,\; dT/dr = 0,\; H = 0, \\ \text{at} \quad r = R \quad T = T_w, \end{gathered} \tag{8}$$

where T_w is the temperature of the channel wall, which is assumed to be equal to 2000°K. The value of the electric field intensity E which satisfies the boundary condition (8) is sought by the iterational method of secants. The total arc current is determined as

$$I = 2\pi E \int_0^R \sigma(r)\, r\, dr.$$

Varying T_0, we obtain the entire volt—ampere characteristic (VAC) of the arc for a fixed value of P_0 with selected v_m and r_m. If it is not specially stipulated, then the results presented refer to a pressure on the axis of $P_0 = 10^5$ Pa.

The computational results corresponding to the gas dynamical method of gas twisting are presented in Figs. 1-5. The azimuthal velocity is described by Eq. (6), and the coordinate of the maximum r_m is chosen equal to $R/\sqrt{3}$. This coordinate, which corresponds to the coordinate of the maximum of the circumferential velocity in the case of electromagnetic rotation of the plasma, is selected for comparison of the results of these twisting methods.

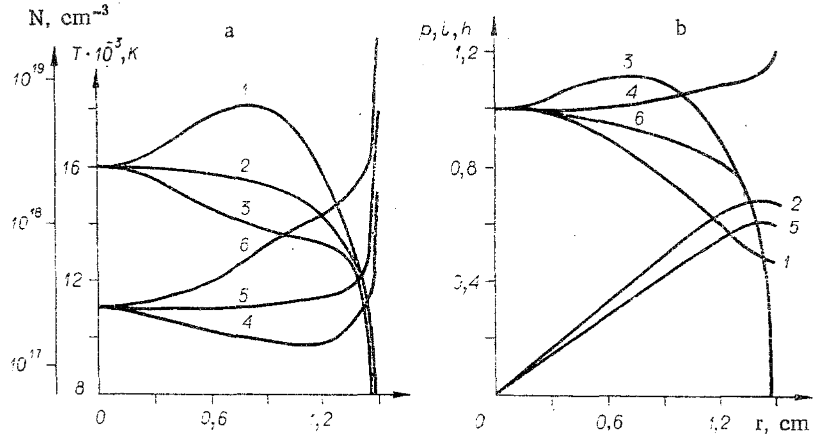

Fig. 1

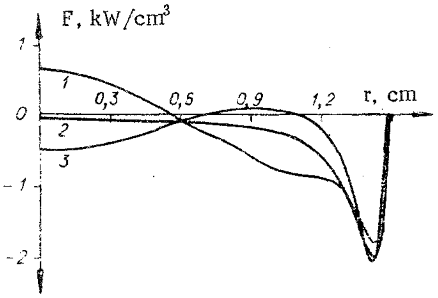

Fig. 2

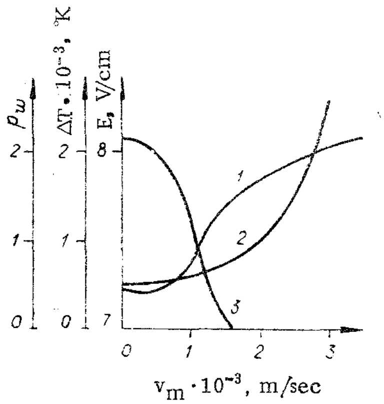

Fig. 3

The effect of plasma rotation on the characteristics of an electric arc burning in a laminar twisted flow of a plasma-forming gas is induced by redistribution of the density in the centrifugal force field. In order that this effect result in appreciable and qualitative changes, rotational velocities comparable with the thermal velocity of the plasma particles v_T or exceeding them are necessary.

The radial distributions of the temperature (curves 1-3) and density (curves 4-6) of the plasma of a rotating arc are shown in Fig. 1a for a channel 3 cm in diameter. Curves 1 and 4 refer to an untwisted arc, curves 2 and 5 refer to an arc twisted with velocity $v_m = 1.8 \cdot 10^3$ m/sec, and curves 3 and 6 refer to an arc twisted with velocity $v_m = 3.5 \cdot 10^3$ m/sec. The distributions of the dimensionless pressure $p = P/P_0$ (curves 1 and 4), the magnetic field $h = H/\sqrt{\mu_0 P_0}$ (curves 2 and 5), and the current density $i = j/j_0$ (curves 3 and 6) are shown in Fig. 1b. Curves 1-3 correspond to an untwisted arc, and curves 4-6 correspond to a rotating arc with $v_m = 2.2 \cdot 10^3$ m/sec.

As shown in [5], there are regions of axial temperatures T_0 for which the radial temperature distributions of a nonrotating arc are nonmonotonic (Fig. 1a, curve 1). As is evident from the radial distribution of the quantity $F = \varepsilon - \sigma E^2$ (Fig. 2, curve 1), the relationship $F > 0$ is satisfied in the axial zone of the discharge. It follows from the condition of maintaining the energy balance that the temperature gradient is positive. The pressure of the plasma drops as the distance from the discharge axis increases (Fig. 1b, curve 1) due to compression of the arc filament by the intrinsic magnetic field of the axial current. The emittance of an Ar plasma in the temperature range 15,000-19,000°K is practically independent of temperature [5]; therefore in view of its strong pressure dependence the quantity $\varepsilon - \sigma E^2$ decreases, and the relationship $F < 0$ is satisfied at some radius. The temperature, having reached its maximum value T_{max}, decreases to the wall temperature. We note that it is impossible to seek nonmonotonic temperature distributions within the framework of the single Elenbaas–Heller differential equation which is widely used to describe an electric arc [2-4].

In the case of small values of the circumferential velocities $v_\varphi^2 \ll v_T^2$, when the twisting exerts no appreciable effect on the arc characteristics, radial stratification of the ions

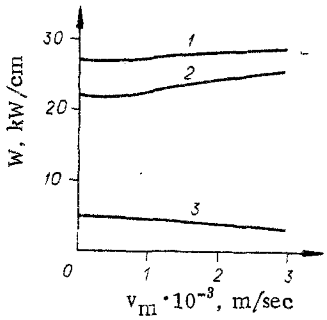

Fig. 4

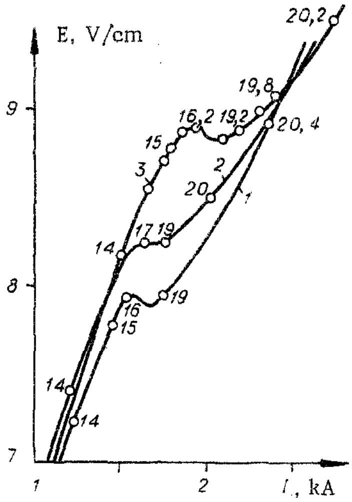

Fig. 5

and atoms with a minimum in the vicinity of r_m (Fig. 1a, curve 4) corresponds to nonmonotonic temperature distributions. By analogy with the flow of a fluid in a gravitational field, one should expect that a negative density gradient is a destabilizing factor in a rotating flow.

In a rotating plasma flow the pressure is nonmonotonic along the radius (Fig. 1b, curve 4). A change in sign of the pressure gradient occurs and a significant increase in pressure towards the periphery is observed in the gas shell of an arc filament, where the centrifugal force dominates the Lorentzian force.

Figure 3 shows the dependence of the electric field intensity E (curve 1), the gas kinetic pressure on the wall p_w (curve 2), and the quantity $\Delta T = T_{max} - T_0$ on the maximum twisting velocity v_m, with the remaining discharge parameters fixed and selected equal to $T_0 = 16{,}000$°K and R = 1.5 cm. The electric field intensity and the boundary pressure p_w increase appreciably in a twisted arc, and the quantity ΔT decreases to zero. Starting from the value $v_m = 1.65 \cdot 10^3$ m/sec, the temperature distribution becomes a monotonically decreasing and the density a monotonically increasing function of the radius (curves 2 and 5 in Fig. 1a). Consequently, a stable spatial stratification of the plasma density is established at all points of the interval [0, R] in an arc burning in a rotational gas flow. A change of the temperature distribution in a twisted arc leads to a redistribution of the current density (Fig. 1b, curve 6) and a decrease of the total current, which is reflected in a smaller value of the magnetic field intensity (Fig. 1b, curve 5). In the case of a larger value of the twisting an anomalously large temperature gradient is observed in the near-axis zone of the arc (Fig. 1a, curve 3). Intense redistribution of the density in a field of centrifugal forces (Fig. 1a, curve 6) has resulted in the fact that a spatial interval occurs within the channel in which the value of F is positive (Fig. 2, curve 3), which is compensated by an increased thermal flow from the central axial zone of the arc. With a moderate amount of twisting the quantity F is positive everywhere, as is evident from curve 2 of Fig. 2, which corresponds to $v_m = 1.8 \cdot 10^3$ m/sec.

The energy contributed to the discharge W_d is drained off by radiation W_r and thermal conductivity W_w:

$$W_d = IE, \quad W_r = 2\pi \int_0^R \varepsilon r dr, \quad W_w = 2\pi \varkappa r \frac{dT}{dr}\Big|_{r=R}. \tag{9}$$

The dependences of the integrated energy characteristics of the arc (9) on the value of the velocity at the maximum v_m are shown in Fig. 4 [curve 1) W_d, 2) W_r, and 3) W_w] for the selected axial temperature $T_0 = 16{,}000$°K. Over a wide range of twisting the Joule heating energy is practically independent of the quantity v_m, but it is redistributed between W_r and W_w. The radiation losses increase, and the conductive thermal flux into the wall decreases.

An increase in the intensity in a rotating arc alters the appearance of its volt–ampere characteristic. This change is especially important in the region of the superheating in-

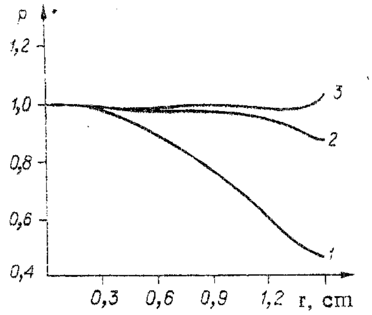

Fig. 6

stability, where the VAC of an untwisted arc contains an N-type loop (Fig. 5, curve 1, R = 1 cm). The discharge conditions corresponding to the declining section of the loop are unstable [2]. One can select twisting parameters v_m and r_m for which the VAC of the arc do not contain a section with negative differential conductivity (Fig. 5, curve 2). Curve 2 in Fig. 5 is the volt—ampere characteristic of a rotating arc in a channel with a diameter of 2 cm having the twisting parameters $v_m = 3 \cdot 10^3$ m/sec and $r_m = 1/\sqrt{3}$ cm which is monotonically increasing. Curve 3 in Fig. 5 is the volt—ampere characteristic of an untwisted arc in the very same channel with $P_0 = 1.5 \cdot 10^5$ Pa. Thus rotation not only stabilizes an arc in space, creating stable stratification of the plasma density in a centrifugal force field, but also suppresses the superheating instability of the discharge. An increase of the radiation loss in a rotating arc resulted in the fact that its volt—ampere characteristics go higher than the VAC for a nonrotating arc, whose radiation losses are smaller.

The difference between the two twisting methods described by Eqs. (6) and (7) consists in the fact that in the second case the velocity on the wall is equal to zero. A comparison of the computational results with the other parameters remaining the same has shown that the main difference involves the radial distributions of the pressure and density (Fig. 6, curves 2 and 3, $T_0 = 16{,}000$°K, R = 1.5 cm). In the thin boundary region where the gas is not electrically conductive the gas kinetic pressure either flattens out, if the circumferential velocity tends to zero (Fig. 6, curve 2), or increases sharply under the action of centrifugal force (Fig. 6, curve 3, and Fig. 1b, curve 4).

One can note the following on the basis of the results outlined above. Rotation of a plasma increases the electric field intensity applied to an arc. With the appropriate choice of twisting parameters, the volt—ampere characteristic of a discharge does not contain a section with negative differential conductivity (loops). This fact indicates that one can contend with the superheating instability of a gaseous discharge using plasma rotation. Rotation creates a stable radial stratification of the plasma density in an arc burning in a twisted flow of plasma-forming gas over the entire range of axial temperatures discussed.

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EFFECT OF THE BLUNT-END RADIUS OF A CONE MOVING IN AIR AT HYPERSONIC VELOCITY ON THE IONIZATION OF THE REGION DISTURBED BY IT

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UDC 532.526

A procedure is expounded in [1] for a global calculation of the region disturbed by an axisymmetric body moving at hypersonic velocity at zero angle of attack with Reynolds numbers $Re_\infty \geqslant 3 \cdot 10^3$ (the number Re_∞ is constructed from parameters in the oncoming flow and the blunt-end radius). The computational procedure is based on taking approximate account of all effects of fundamental importance to the formation of the flow field, namely: nonequilibrium physicochemical processes in the entire disturbed region, transport processes near the surface of the body and in the distant wake, viscous drag of the gas, and a decrease (in the case of a cold wall) of the total enthalpy in the viscous subregion of the near wake. The procedure is justified both by considerations of a physical nature and by experimental and theoretical data existing in the literature [1-4].

The procedure for calculation of the wake behind a body in [1] includes a calculation of the viscous subregion of the near wake and assumes the use as initial data of the distributions of the parameters of a mixture of gases near the cutoff of the body obtained with the transport processes near the lateral surface of the body taken into account (and also the inflow of foreign gases from the surface of the body if this occurs). As a result the procedure of [1], in contrast to other procedures, is applicable to the calculation of the wakes behind bodies with any blunt-end radius.

The characteristic peculiarities of the effect of the blunt-end radius of a moving body on the ionization of the flow field are investigated in this paper on the basis of an analysis of the computational data obtained with the use of the procedure of [1]. A discussion is conducted with the example of the motion of spherically blunt cones with apex half-angle 10° and length 1.5 m in the atmosphere of the Earth at an altitude of 50 km with velocity 7.4 km/sec. It is assumed that the surface of the cones is ideally catalytic and its temperature is 1000°K. Inflow through the surface and disintegration of the surface of the body are absent.

The system of physicochemical processes used in the calculations is given in [1]. An effective sticking process was additionally taken into account according to the data of [5] in connection with the calculation of the wake.

Let us first dwell on the question of the effect of transport processes on the formation of the plasma parameters near the lateral surface of the body. Computational data on the distribution of the electron density and temperature near the cutoff of the cones for the cases r_0 = 15 and 60 cm, respectively (r_0 is the blunt-end radius), are given in Figs. 1 and 2. The dashed curves denote a calculation without transport processes taken into account (according to the procedure of [4]), and the solid curves denote a calculation with the boundary layer taken into account (according to the procedure of [2]). The electron density axis n is shown at the top, and the temperature axis t in units of 1000°K is at the bottom. The coordinate normal to the contour of the body is plotted along the ordinate.

Leningrad. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 4, pp. 12-16, July-August, 1981. Original article submitted June 10, 1980.

 0021-8944/81/2204-0448$07.50