PARAMETERS OF A CLOSED ARC STABILIZED BY A LONGITUDINAL FLOW OF ARGON

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This article sets forth the results of an investigation of the temperature, velocity, dynamic head, and static pressure in high-current argon arcs used in plasma metallurgy. It is shown that the velocity and the amount of gas pumped through the column of the arc are determined by the current of the arc. A calculation is made and equations are presented which permit calculating this type of arc on the basis of a simplified equilibrium model. Experiment is compared with theory.

An arc discharge at atmospheric pressure, with a strong current on the order of several kiloamperes, obtained in a plasmotron with axial feed of a stabilizing gas, is a basic new method for the plasma-arc melting of various metals and alloys. The possibility of melting in an atmosphere of inert gas with nonconsumable electrodes and a minimum of contaminations makes it possible to obtain high-quality metal in such units. The process of plasma-arc melting and the plasmotron are shown schematically in Fig. 1. The parameters of the column of such an arc stabilized by a flow of gas are required for the choice of optimal conditions for the industrial process.

An experimental study was made of an arc with a length of 100 mm, burning between a water-cooled tungsten cathode with a diameter of 10 mm and a copper anode. An axial flow stabilizing the argon arc was fed into the annular gap between the cathode and a nozzle with a diameter of 16 mm. The arc burned vertically from the top downward (the cathode above, the anode below). The cathode was arranged vertically at the outlet cross section of the nozzle. The column of the arc was studied under the following conditions: current strength I = 600, 800, 1000, 1400 A; mass flow rate of stabilizing gas G = 1, 2, 3, 4 g/sec.

The following parameters were measured: the temperature field of the arc T(r, z); the velocity head and the static pressure in the column of the arc P(r, z), P_0; v and ρv were then determined from the measured values of P and T.

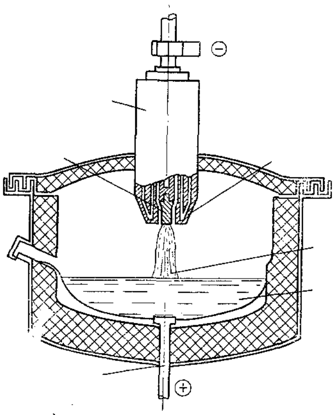

Fig. 1

The temperature of the arc was measured by a spectral method from the absolute and relative intensities of the spectral lines (Ar I = 4040, 4251, 4345 Å; Ar II = 4013, 4348, 4806 Å) and from the absolute intensity of the recombination continuum in the region 4500 Å. Use was made of the probabilities of transitions and of the recommendations on measurement of the temperature by spectral methods contained in [1-3].

For measurement of the velocity head and the static pressure in the arc, a method [4] and a special pickup have been developed. An uncooled Pitot tube, connected using special packing to the sensitive membrane of a condenser-type microphone, was shot through the arc column using a magnetic device. The signal of the pressure sensed by the receiving opening of the Pitot tube was transmitted pneumatically to the membrane and, using a special scheme, was shaped to the form of an electric pulse which was recorded on the screen of an oscillograph. The velocity at which the

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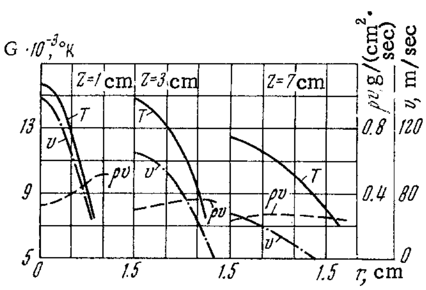

Fig. 2

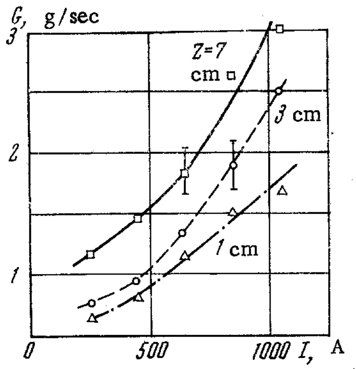

Fig. 3

pickup was shot through was ~0.5 m/sec; it was selected from the condition of the thermal resistance of the Pitot tube.

The signal of the pressure was calibrated with respect to a micromanometer in a cold flow. The sensitivity of the scheme permitted recording a change in the pressure of ~10 dyn/cm^2. The spatial accuracy of the measurements was determined by the receiving opening of the Pitot tube and was ~2 mm. A special disk-type adapter, connected with the membrane of an uncooled tube, was used to measure the static pressure. The plane of the disk was displaced parallel to the axis of the arc, which eliminated the effect of the velocity head on the receiving opening.

The accuracy in measurement of the head was ~5% at the axis of the column and ~25% at the periphery of the arc.

The frequency characteristic of the pickup, its sensitivity, and the errors in the measurements are expounded in detail in [4].

The total pressure recorded by the pickup P_Σ is the sum of the velocity head of the plasma, $\rho v^2/2$, and the static pressure in the column of the arc P_0, which consists of the magnetic "pinch-effect" and the residual pressure in the chamber (the latter was almost always equal to 1 atm)

$$P_\Sigma = {}^1/_2 \rho v^2 + P_0 \, .$$

If P_Σ and P_0 are known from measurements and $T \rightarrow \rho$, then, on the basis of this equality, the velocity of the plasma can be determined:

$$v = \sqrt{\frac{2(P_\Sigma - P_0)}{\rho}} \, .$$

The static pressure in the column of the arc can be calculated if the law of change in the current density j(r) is known. For monitoring and evaluation of the measured values of P_0, a theoretical calculation of this value was made for a parabolic distribution of the current over the radius:

$$j(r) = j_0 (1 - r^2/R^2) \, .$$

For such a distribution, the axial value $P_0(0)$ is connected with the total current of the arc by the following equation:

$$P_0(0) = \frac{\mu_0}{4\pi} \frac{5I^2}{3\pi R^2} \, .$$

The results of measurements of the axial values of the temperature T, the total pressure P_Σ, and the static pressure P_0, the velocity head P_V in the column of the arc, as well as calculations of v and ρv for a cross section of the arc located at a distance of 3 cm from the cathode, for G = 2 g/sec with different currents, are presented in Table 1.

The results of measurements of the radial distribution of several quantities in different cross sections along the length of the arc are shown in Fig. 2. The temperature at the axis of the arc falls appreciably with increasing distance from the cathode. The profile of T(r) in the cross section z_3 = 7 cm differs appreciably from the profile of T(r) in the cross section z_1 = 1 cm. This circumstance is connected with the increase in the diameter of the column of the arc from the cathode toward the anode and with a decrease in the current density at the axis. Measurement of the velocity head showed that in such arcs, the value of $\rho v^2/2$ itself, in comparison, for example, with plasmotrons for cutting metals, is small. However, the velocity head and the velocity of the gas flow (Table 1, Fig. 2) depend strongly on the total current of the arc I. Thus, with an increase in the current from 600 to 1400 A, the velocity at the axis increases by almost twice, and the dynamic head by 2.5 times.

A significant increase in the current strength in such arcs can lead to a substantial rise in the dynamic head and to spattering of the metal bath. Precisely for this reason, in some cases it is possible to limit the increase in the current and the power of the melting plasmotrons.

TABLE 1. Axial Values of Parameters of Arc, G_0 = 2 g/sec

I, A	T, °K	P_Σ, N/m²	P_0, N/m²	P_v, N/m²	v, m/sec	$\rho v(0)$, cm²/sec	G, g/sec
600	13200	200	120	80	70	0.22	0.6
800	13500	250	140	110	83	0.26	0.75
1000	13800	300	180	120	95	0.27	1.2
1200	14100	400	240	160	110	0.30	1.7
1400	14500	520	200	220	130	0.34	2.3

It is of interest to evaluate the total amount of gas G captured in the column of the arc, related to the mass flow rate of the stabilizing gas G_0. To determine the value of G, a summation was made of the distribution of ρv in different cross sections of the arc at different currents:

$$G = 2\pi \int_0^R r\rho v dr \cdot$$

The radius of the arc was determined from the isotherm T ≈ 7000°K.

The results of such a summation, for a mass flow rate of 2 g/sec, are shown in Fig. 3. It is evident from the figure that the total mass flow rate of the gas through the column of the arc depends strongly on the current strength I. With a change in the current strength from 600 to 1400 A, G increases by 3 times. This is a result both of a rise in the velocity of the gas and of an increase in the cross section of the arc, limited by the isotherm T ≈ 7000°K. The value of G does not remain constant over the length of the column of the arc, which is connected above all with an increase in the diameter of the arc as it approaches the anode.

From this point of view, it is possible to explain a certain spatial instability of the arc near the anode. At a given mass flow rate of the stabilizing gas G_0, with its motion away from the cathode an ever greater amount of this gas is captured in the arc, and an ever lesser amount remains for stabilization.

Near the anode it may turn out that all the gas G_0 is captured in the column of the arc and that there is no stabilizing gas curtain. In this case a spatial instability of the arc in the anode zone appears, and the working conditions of the plasmotron become unstable. This latter circumstance may also be connected with the magnetohydrodynamic instability of the column of the arc itself, as well as with the turbulence of the stabilizing jet of cold gas. The strong capture of stabilizing gas cannot be ignored with an increase in the current. As follows from Fig. 3, with currents of 1500 A in the given construction of a plasmotron, the amount of gas stabilizing the arc should not be less than 3 g/sec.

From the point of view of the capture of cold gas, the arc behaves like an electromagnetic pump. It was remarked in [5] that the amount of gas captured by the arc is determined by the conical form of the arc and the associated gradient of the static pressure, which drives the gas from the cathode to the anode.

The same type of mechanism acts also in melting arcs. This is why an increase in the current strength (and of the gradient of the static pressure) leads to such a strong increase in the velocity, in the velocity head, and in the amount of gas captured by the arc.

The radial distribution of the mass flow rate (Fig. 2) indicated that, in a cross section close to the cathode, the gas blows and stabilizes the column of the jet. With increasing distance from the cathode, an ever greater amount of gas is captured by the arc, the distribution of ρv becomes flat, and, in cross sections close to the anode, with a small error, it may be assumed that ρv = const. It must be noted that the distribution of ρv(r) along the whole length of the arc does not differ too much from ρv(r) = const. This, by the way, provides a basis, in the further calculation of an arc, for assuming that

$$\rho v = \text{const} = G_0/\pi R^2 \cdot$$

Measurement of the value of $P_0(0)$ in an arc using a disk-type adapter gives values which are approximately 2 times lower than the calculated values. This circumstance may be connected, in the first place, with the low accuracy of measurements of the static pressure by this method and, in the second place, with a different distribution of the current which, in fact, differs from the parabolic distribution assumed in the calculation. The results of measurements of the distribution of $P_0(r)$ indicate that the real current radius R of the arc is obviously somewhat greater than the radius adopted in the calculation, which corresponds to the isotherm $T \approx 7000°K$. The low accuracy in measurement of $P_0(r)$ at the present time forces us merely to mention these effects without an analysis of their quantitative aspect. For just this reason, calculated values of P_0 were used everywhere in calculation of v and ρv.

Measurements of the degree of turbulence over a cross section of the column of the arc, made using a special turbulence meter, permit drawing the conclusion that the flow in the column of the arc has a laminar character. The degree of turbulence, determined as the ratio of the mean pulsation component of the velocity $\bar{v}'$ to the mean value of the directed velocity $\bar{v}_z(\varepsilon = \bar{v}'/\bar{v}_z)$, from measurements at the axis and at the edge of the column of the arc in the cross section z = 3 cm, has the values 0.02 and 0.10, respectively. The existing pulsations are in all probability connected with instability of the anode and cathode spots and with pulsations in the feed source. Their frequency lies in the range 100-300 Hz. The limited possibilities of the turbulence meter did not permit measuring the frequency of pulsations above 1000 Hz. These measurements, in a subsequent calculated explanation of the results obtained, permitted using a laminar model of the arc.

To compare the data obtained with the theory of an equilibrium plasma, a calculation was made for the column of an arc in an infinite flow of gas.

If the properties of the gas, in an atmosphere of which the arc is burning, are known functions of the temperature and the pressure, the parameters of an arc at thermal equilibrium are determined by simultaneous solution of the differential equations of energy and motion. These equations were solved by introducing simplifying assumptions, the most important of which are the assumption of the steady-state nature of the process of the homogeneous and laminar character of the motion of the gas, of the constancy of ρv, c_p/λ, and μ, of the absence of self-absorption of radiation, and of the incompressibility of the gas in the volume of the conducting zone of the arc column. The above equations can be represented in the following form:

$$\sigma E^2 = U_r + \rho v_z c_p \frac{\partial T}{\partial z} - \frac{1}{r}\frac{\partial}{\partial r}\left(r\lambda \frac{\partial T}{\partial r}\right) \quad (1)$$

$$\rho v_z \frac{\partial v_z}{\partial z} = -\frac{\partial P_{\text{ст}}}{\partial z} + \mu_0 j_r H_\varphi + \mu\left(\frac{\partial^2 v_z}{\partial r^2} + \frac{1}{r}\frac{\partial v_z}{\partial r}\right) \quad -\frac{\partial P}{\partial r} + \mu_0 j_z H_\varphi = 0 \quad (2)$$

where T and v_2 are the temperature of the gas; σ, μ_0, λ, μ, c_p, ρ are the specific electrical conductivity, the magnetic permeability, the coefficient of thermal conductivity, the coefficient of dynamic viscosity, the specific isobaric heat capacity, and the density of the gas, respectively. U_r is the energy of the radiation; E and H are the intensities of the electric and magnetic fields; j is the current density; P is the pressure of the gas in the arc.

To solve the equation of energy (1), we introduce the function

$$S = \int_0^T \lambda dT \cdot$$

The intensity of the electrical field is expressed in terms of the current of the arc

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

The properties of the gas σ(S) and U_r(S) are approximated by the straight lines

$$\sigma = \begin{cases} 0 & \text{at} \quad 0 \leqslant S \leqslant S_1 \\ B(S - S_1) = BS^* & \text{at} \quad S_1 \leqslant S \leqslant S_0 \end{cases}$$

$$U_r = \begin{cases} 0 & \text{at} \quad 0 \leqslant S \leqslant S_1 \\ A(S - S_1) = AS^* & \text{at} \quad S_1 \leqslant S \leqslant S_0 \end{cases}$$

where S_0 are the values of the function at the axis of the arc.

The conical character of the arc in its initial section is taken into consideration using the relationship $R(z) = R_0 f(z)$, where R(z) is the instantaneous radius of the arc; $R_0 = R|_{z \to \infty}$; and $f(z)$, in the interval $0 < z < \infty$, is a continuous differentiable function, rising monotonically from 0 to 1. The radius of the arc in the initial cross section at the surface of the cathode $R_k = R|_{z=0}$ is assumed to be known from experiment and to be equal to the radius of the cathode spot. The function $B(S_0)$, which varies only slightly,

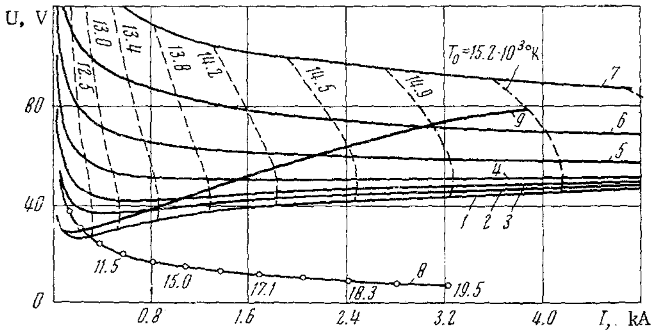

Fig. 4

is assumed to be constant in the volume of the arc. The infrequent increase of the function $A(S_0)$ in the direction from the anode toward the cathode is taken into account by the relationship

$$A = A_0 \frac{R_0^2}{R^2} \quad (A_0 = A(S_0)\big|_{z\to\infty})$$

Taking into consideration what has been said, we can write Eq. (1) in the form

$$I^2 B\left[\int_0^R 2\pi r S^* dr\right]^{-2} = AS^* \frac{R_0^2}{R^2} + \rho v_z \frac{c_p}{\lambda}\frac{\partial S^*}{\partial z} - \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial S}{\partial r}\right) \tag{3}$$

and the boundary conditions of the problem in the form

$$S^*(RZ) = 0, \qquad \overset{*}{S}(rz_0) = 0\ . \tag{4}$$

A solution of the quasilinear parabolic equation (3) with homogeneous boundary conditions (4) can be obtained in the form

$$S^* = S_{00}^* \psi_n\left(\frac{r}{R} z\right) J_0\left(\gamma_1 \frac{r}{R}\right) \tag{5}$$

where

$$S_{00}^* = S_0^*\big|_{z\to\infty} = \frac{\gamma_1}{2\pi J_1(\gamma_1) B^{1/2}[A_0 R_0^2 + \gamma_1^2]^{1/2}} \frac{I}{R_0}\ .$$

$J_0(x)$ is a Bessel function of zero order of the first kind; $\gamma_1 = 2.405$ is the first root of this function, and $J_1(x)$ is a Bessel function of the first order of the first kind. If

$$f(z) = \left\{1 - \exp\left[\frac{2(A_0 R_0^2 + \gamma_1^2)}{R_0^2 \rho v_z c_p/\lambda} z\right]\right\}^{1/2}, \tag{6}$$

then

$$\psi_n\left(\frac{r}{R} z\right) = \left\{\frac{1 - f^2(z)}{[f^2(z)]^{n+1}}\left[\int \frac{[f^2(z)]^{n-1} d[f^2(z)]}{[1 - f^2(z)]^2} + C_1\right]\right\}^{1/2}; \tag{7}$$

the parameter n is determined by the equality

$$nJ_0\left(\gamma_1 \frac{r}{R}\right) = \gamma_1 \frac{r}{R} J_1\left(\gamma_1 \frac{r}{R}\right)\ .$$

The integral in the right-hand part of expression (7) can be expressed in finite form in terms of elementary functions for a denumerable set of values of the parameters n, determined by the expression $N = n_1 + 1/n_2$ ($n_1 = 0, 1, 2, \ldots$; $n_2 = 1, 2, 3, \ldots$).

Equalities (5) and (7) are the solution to the problem of calculating the temperature field of the arc, since they permit finding the value of the function S^* at any given point of the conducting zone.

For points lying at the axis of the arc

$$\psi_n\left(\frac{r}{R}, z\right)\Big|_{n=0} = \psi_0(z) = \left\{\frac{1 - f^2(z)}{f^2(z)} \ln \frac{f^2(z)}{1 - f^2(z)} + \frac{1 - f^2(z)}{f^2(z)} C_1 + 1\right\}^{1/2}$$

where

$$C_1 = \ln \frac{1-\bar{R}_k^2}{\bar{R}_k^2} - \frac{\bar{R}_k^2}{1-\bar{R}_k^2}, \qquad \bar{R}_k = \frac{R_k}{R_0} .$$

On the basis of these equalities, we can obtain expressions determining the current, the intensity of the electrical field, the voltage of the arc, as well as the heat losses from the column by radiation, thermal conductivity, and convection. The unknown quantities in the above expressions are the local mass flow rate of the gas ρv_2 and the radius of the arc at infinity R_0.

It has already been pointed out that the conical form of the arc leads to the appearance in the column of the axial components of the ponderomotive forces and of the pressure gradient of these forces $\partial P/\partial z$, which brings about a directed motion of the gas in the column. In this case, the initial section of the arc resembles an electromagnetic pump, sucking gas from the surrounding medium and driving it through the column in the direction of the anode.

An evaluation of the relative value of the forces of inertia and viscosity shows that, at the axis of the arc, the viscosity forces are considerably less than the inertial forces while, at the periphery, the forces of viscosity and inertia are commensurate. This result permits regarding the surface $r = R$ as a quasi-solid wall, separating the arc from the external medium and transmitting from the surrounding medium into the arc only that amount of gas which the "electromagnetic pump" is capable of pumping.

As a result of solution of the equation of motion (2), the following expression is obtained for the local mass flow rate of the gas in an arc with a length l :

$$\rho v_z = \left[\frac{\gamma_1 \mu_0 I^2}{16\pi^2 J_1(\gamma_1) R_0^2} \rho_{0l} F(l)\right]^{1/2} \tag{8}$$

where $F(l) = F(z)\big|_{z = z_0 + l}$.

$$F(z) = \frac{1}{f^2(z)}\left[\frac{1-f^2(z)}{f^2(z)}\right]^t \left\{\ln f^2(z) + \frac{t}{2}[\ln f^2(z)]^2 + t\frac{\pi}{3}\arcsin f^2(z)\right\} + C_2$$

$$C_2 = -\ln \bar{R}_k^2 - \frac{t}{2}[\ln \bar{R}_k^2]^2 - t\frac{\pi}{3}\arcsin \bar{R}_k^2$$

$$t = \frac{\gamma_1^2}{2}\frac{\mathrm{Pr}}{A_0 R_0^2 + \gamma_1^2} .$$

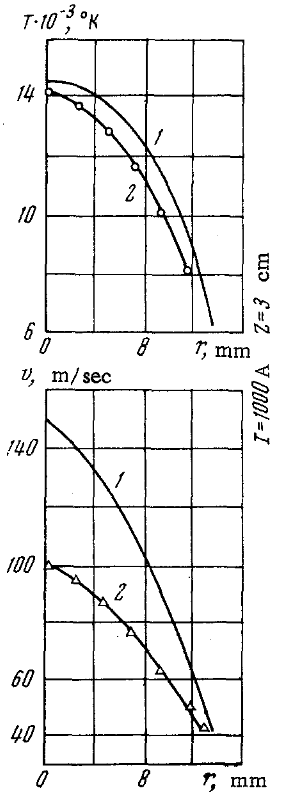

Fig. 5

Pr is the Prandtl number; ρ_{0l} is the density of the gas at the axis of the arc in the cross section $z = z_0 + l$.

In accordance with equation (8), the velocity of the motion of the gas in the arc rises rapidly with an increase in the current.

The radius of the arc R_0 can be determined by regarding the column of the arc as a solid body, whose heat exchange with the surrounding medium in a field of gravitational forces is described by the dimensionless relationship $\mathrm{Nu} = C(\mathrm{Gr})^{1/3}\mathrm{Pr}^{1/2}$, where $C = 3$, and Nu, Gr are the Nusselt and Grashof heat-transfer numbers, respectively. The determining temperature, at which the properties of the gas are substituted into the expression $T^* = (T_1 + T_\infty)/2$. Here T_1 is the temperature at the surface $r = R$, and T_∞ is the temperature of the surrounding medium.†

On the basis of the above model, calculations were made of the temperature field, the velocity of the motion of the gas, and the volt–ampere characteristic of an arc with a length of 100 mm, with G = 2 g/sec. Figure 4 gives the values obtained from the calculation for the volt–ampere characteristics of such an arc, with (curves 1-7) and without (curve 8) taking account of radiation. Characteristics 1-7 were obtained for different values of the mass flow rate of the gas G through the column of the arc [1) G = 0; 2) 0.5; 3) 1; 4) 2; 5) 4; 6) 8; 7) 16; 8) 5 g/sec]. It is evident that taking account of radiation and of heating

† This assumption is extremely rough, and the main divergences between theory and experiment are obviously connected with it.

of the gas raises considerably the volt–ampere characteristics of the arc. The same figure shows the experimental curve 9 ($G_0 = 2$ g/sec), which intersects the calculated curves 1-7. This circumstance is explained by the fact that, with an increase in the force of the current, the column of the arc captures an ever greater amount of gas; therefore, under real conditions, the parameter G does not remain constant with a change in I.

The curves (Fig. 4) were calculated for the condition $T_\infty = 273°K$ and therefore differed from the conditions of the experiment, in which $T_\infty > 500°K$. The quantity T_∞ exerts an effect on the whole profile of T(r), which leads to a certain increase in the experimental value of G and to a certain displacement of the curves (Fig. 4). A comparison between experimental values of G_e (Fig. 3) and calculated values of G_t, after the introduction of a correction for T_∞, furnishes a satisfactory explanation for the dependence of the value of G on the current (see below).

I, A	500	1000	1500
T_∞	200	350	700
G_t, g/sec	0.68	1.54	1.65
G_e, g/sec	0.85	1.70	2.2

Figure 5 gives distributions of T(r) and v(r), obtained from calculation (1) and measured (2) (I = 1000 A; z = 3 cm; G = 2 g/sec). The agreement is satisfactory for v(r) and good for T(r). It is clear from what has been said that the proposed calculation model, in spite of all the simplifications and assumptions, permits a sufficiently simple analytical calculation of the open arc of a melting plasmotron, with a good approximation to the real parameters with respect to the temperature and a satisfactory approximation with respect to the velocity.

The calculation also confirms one of the principal results of the experiment, in accordance with which a conical open arc constitutes an "electromagnetic pump," pumping an amount of gas proportional to the strength of the current.

LITERATURE CITED

1. W. Gericke, "Messung der Ubergangs-wahrscheinlichkeit sowie Halbwertbreite und Vershiebung von Al-Linien in thermisch leuchtenden Plasmen," Z. Astro-Phys., 53, No. 1 (1961).
2. H. N. Olsen, "Measurement of argon transition probabilities using the thermal arc plasma as a radiation source," J. Quant. Spectrosc. and Radiat. Trans., 3, No. 1 (1963).
3. V. M. Gol'dfarb, "Simple method for determining the temperature and the electron concentration of a one-component plasma," Optika i Spektroskopiya, 19, No. 2 (1965).
4. A. A. Voropaev, S. V. Dresvin, and V. S. Klubnikin, "Measurement of the flow velocity of a plasma using a total-pressure tube," Teplofiz. Vys. Temp., 7, No. 4 (1969).
5. A. A. Voropaev, V. M. Gol'dfarb, A. V. Donskoi, S. V. Dresvin, and V. S. Klubnikin, "Thermal and gas-dynamic characteristics of an arc discharge in a longitudinal flow of argon," Teplofiz. Vys. Temp., 27, No. 3 (1969).