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STUDY AND GENERALIZATION OF VOLT — AMPERE AND THERMAL CHARACTERISTICS OF A TWO-JET PLASMOTRON

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The construction of a two-jet plasmotron is worked out. Its thermal and electrical characteristics are studied. The volt — ampere characteristics and thermal efficiency are generalized.

Two-jet plasmotrons find application in plasma chemistry, in plasmathermy, and in processes of treatment of disperse materials [1-3]. A peculiarity of two-jet plasmotrons is the presence of an open semicompressed electric arc and two combining plasma streams directed at an angle to one another. The absence of engineering equations for the calculation of two-jet plasmotrons hinders their most rapid introduction into industry.

In the present report we begin comprehensive studies of the design of two-jet plasmotrons and the plasma streams produced by them for the development of industrial constructions.

The two-jet plasmotron studied is analogous in construction to that described in [4, 5]. The arc ignition system and the design of the electrode units are original. A diagram of the design of the two-jet plasmotron and the electric arc ignition system are presented in Fig. 1.

The length of the arc is limited by the construction of the anode unit of the two-jet plasmotron which permits only slight axial movement of the anode spot. The construction of the anode unit resembles the construction of the inner electrode of a one-chamber plasmotron; the anode itself is copper and water cooled. The cathode is of the end type, copper — zirconium, and water-cooled. To fasten the electrode units of the two-jet plasmotron we developed a device making it possible to vary the distance L between the electrode units of the two-jet plasmotron and their angles of inclination to the line of centers within wide limits during operation. In the course of operation the distance L between electrode units was varied in the range of $(2-7) \cdot 10^{-2}$ m and the angles of inclination α_1 and α_2 from 15 to 60°.

Ignition of the electric arc is accomplished with an oscillator; the ballast resistance R (Fig. 1) was used to limit the current strength at the moment of ignition of the arc.

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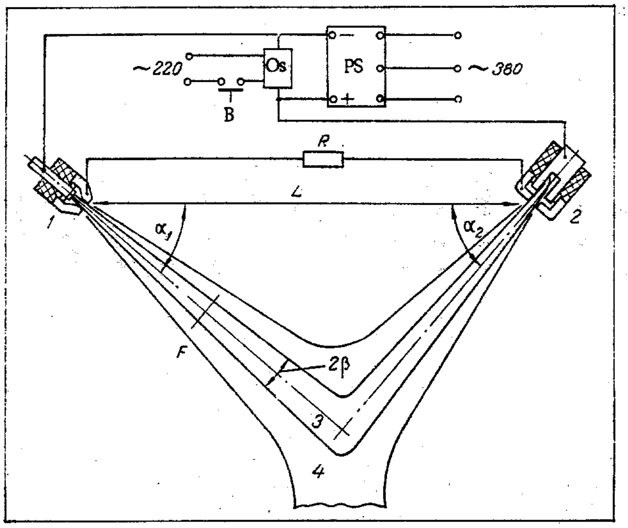

Fig. 1. Diagram of design of two-jet plasmotron and electric arc ignition system (PS: power supply; Os: oscillator; B: ignition button; R: ballast resistance); 1) cathode unit; 2) anode unit; 3) open electric arc; 4) plasma streams.

The two-jet plasmotron was supplied from a direct-current source with a no-load voltage of 600 V. The current strength varied from 80 to 250 A. The power required in the experiments did not exceed 90 kW.

Measurements were made of the volt — ampere characteristics (VAC), the heat fluxes to the electrode units, and the potential distribution over the cross section and along the axis of the arc.

Recorders of type ÉPP-09 and N-700 loop oscillographs were used to measure the VAC of the two-jet plasmotron. Estimates showed that the error in measuring the current strength and burning voltage of the arc of the two-jet plasmotron did not exceed ±5%.

The temperature of the cooling water was measured with preliminarily calibrated six-junction Chromel — Copel thermopiles connected in a differential circuit. The temperatures of the cooling water were recorded by an N-700 type loop oscillograph. The flow rate of the cooling water was monitored with flowmeters and a measuring vessel. The error in the determination of the heat fluxes to the electrode units did not exceed ±10%.

A probe method analogous to that described in [6] was used to measure the potential of the arc relative to the electrodes. The difference consists in the fact that two tungsten filaments 0.3 mm in diameter intersected the arc simultaneously for an increase in the accuracy of the results. The potential of the intersected section relative to the electrodes was recorded by a CI-18 oscillograph. A device was developed which made it possible to impart a velocity $v = 0.6$-1.0 m/sec to the probes. The error in the determination of the potential of the arc relative to the cathode, due to the error of the recording instrument, the error of the system for inserting the probes, and effects near the probes, did not exceed ±10%. By intersecting the arc in different cross sections one can obtain a picture of the distribution of the arc potential along the radius and along the axis. Knowing the distance between the sections being studied and their distance from the electrode units, one can determine the radial and axial electric field strengths of the arc of the two-jet plasmotron.

Generalization of Volt — Ampere Characteristics

The generalization of the VAC is an important task, since it allows one to perform an engineering calculation of two-jet plasmotrons. Two principal courses for the generalization of VAC have been charted at present: in dimensionless criteria [7-9] and in dimensional complexes [2, 9, 11-15].

The advantage of the generalization of VAC in dimensionless criteria consists in the fact that this method allows one to calculate the VAC of plasmotrons with different plasma-forming gases, since the values of σ_0 and h_0 enter into the criteria. However, this also involves a major complication, since it is impossible to exactly select the scaling value of the electrical conductivity for the boundary conditions. In [7] a means is suggested for selecting the controlling values of σ_0 and h_0 through a power-law approximation of the dependence $\sigma_0 = f(h_0)$ at atmospheric pressure. Interpretation of VAC by the criterial functions presented gives a low accuracy (up to 100%).

The generalization of the VAC by the method of dimensional complexes is very effective for plasmotrons using a plasma-forming gas of the same chemical composition [10]. In [2, 9, 11-15] functions are presented for the VAC of plasmotrons of axial design connected with direct and reverse polarities and with air used as the plasma-forming gas. The accuracy of the generalizing expressions is quite high (±15%). An advantage of this method is the simplicity and convenience of use for practical calculations, while a drawback is that one must change the coefficients and exponents in the generalizing equations in the transition from one plasma-forming gas to another.

The aim of the present report was to obtain relatively precise generalizing functions for the VAC, allowing one to perform an engineering calculation of two-jet plasmotrons with an air arc. Therefore, the method of generalization of the VAC in dimensional complexes was taken as the basis.

In [11-13] it is shown that for an air arc the VAC equation has the form

$$U = A\left(\frac{I^2}{Gd}\right)^m \left(\frac{G}{d}\right)^n (pd)^p, \tag{1}$$

where A, m, n, and p are the coefficient and exponents, respectively, which depend on the construction characteristics of the plasmotrons, the connection polarity, the type of current, and the chemical composition of the plasma-forming gas.

In the studies conducted the complexes were varied in the following ranges: for the cathode unit $I^2/G_1 d_{n.c.} = (6.8\text{-}410)\cdot 10^8\ A^2\cdot sec/kg\cdot m$, $G_1/d_{n.c.} = (3.7\text{-}23)\cdot 10^{-2}$ kg/sec·m, $pd_{n.c.} = (4\text{-}8)\cdot 10^2$ N/m; for the anode unit $I^2/G_2 d_{n.a.} = (4.1\text{-}280)\cdot 10^8\ A^2\cdot sec/kg\cdot m$, $G_2/d_{n.a.} = (3.5\text{-}24)\cdot 10^{-2}$ kg/sec·m, $pd_{n.a.} = (5\text{-}10)\cdot 10^2$ N/m.

It did not seem possible to generalize the VAC of a two-jet plasmotron from Eq. (1) alone. This is explained by the fact that the expression presented above does not allow for the possibility of varying the distance L between the electrode units and the angles of inclination α_1 and α_2 of the electrode units to the line of centers, as well as the fact that the flow rates of the plasma-forming air through each electrode unit are practically independent. Therefore, the following method is proposed for the generalization of the VAC of a two-jet plasmotron.

1. The electric arc of the two-jet plasmotron is arbitrarily divided into three sections: a) the voltage drop U_1 within the cathode unit: the intracathode section; b) the voltage drop U_2 within the anode unit: the intra-anode section; c) the voltage drop U_3 over the open part of the electric arc.

2. The voltage drops in each section of the electric arc were generalized in the form of dimensional complexes.

3. The voltage drop over the entire length of the electric arc — the voltage drop U_0 of the two-jet plasmotron — was determined as the sum of the voltage drops over the three sections:

$$U_0 = U_1 + U_2 + U_3. \tag{2}$$

Let us examine the voltage drop in each section of a two-jet plasmotron separately.

Intracathode Section

In construction the cathode unit consists of a one-chamber plasmotron of axial design with gas-vortex stabilization of the electric arc. The processes taking place in the intracathode section differ somewhat from the analogous processes in one-chamber plasmotrons of the usual construction since an anode spot is absent. This explains the need for variation of the numerical coefficients and exponents in the equations for the VAC (1).

There are a number of equations in dimensional complexes describing the VAC of plasmotrons with end-type cathodes for connection in direct polarity and operation on air. The closest to the studies being conducted in terms of the conditions of use are the equations presented in [9]

$$U = 1290\left(\frac{I^2}{Gd}\right)^{-0.15}\left(\frac{G}{d}\right)^{0.30}(pd)^{0.25} \tag{3}$$

and [12]

$$Ed = 4.21\cdot 10^{-2}\left(\frac{G}{d}\right)^{0.15}(pd)^{0.13}\left(355\,\frac{I}{d} + 5.13\cdot 10^{-3}\,\frac{I^2}{d^2}\right). \tag{4}$$

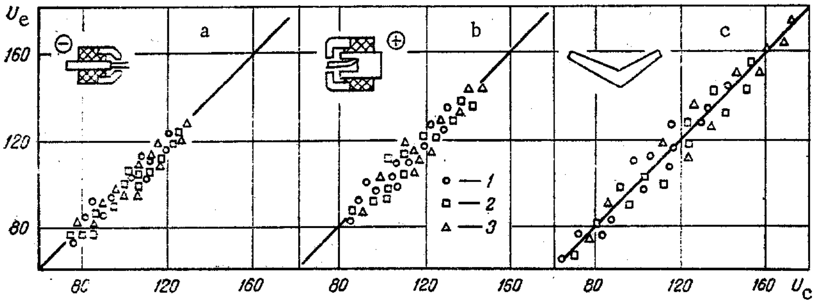

Fig. 2. Experimental values of voltage drop (U_e, V) and generalized VAC (U_c, V) for: a) intracathode section; b) intra-anode section; c) section of open electric arc; 1) $L = 3 \cdot 10^{-2}$ m; 2) $4 \cdot 10^{-2}$; 3) $5 \cdot 10^{-2}$.

The results of the treatment of the experimental data by Eqs. (3) and (4) allow one to note that Eq. (3) agrees somewhat better with the conditions of the experiments being conducted. As indicated above, however, the numerical coefficient and the exponents vary.

The following equation, found for the VAC of the intracathode section of the two-jet plasmotron, agrees well with the experimental results:

$$U_1 = 490 \left(\frac{I^2}{G_1 d_{\text{n.c.}}}\right)^{-0.10} \left(\frac{G_1}{d_{\text{n.c.}}}\right)^{0.25} (pd_{\text{n.c.}})^{0.25}. \tag{5}$$

It is seen from Eq. (5) that the voltage drop in the intracathode section of the two-jet plasmotron depends less on the air flow rate and more on the current strength than in plasmotrons of the usual system (3). Values of U_1 determined experimentally and calculated from Eq. (5) are presented in Fig. 2a.

Intra-Anode Section

The anode unit of the two-jet plasmotron is constructed similarly to a one-chamber plasmotron connected with reverse polarity (the inner electrode is the anode). As the initial equations for the voltage drop of the intra-anode section one can take the equations presented in [10]

$$U^- = 1970 \left(\frac{I^2}{Gd}\right)^{-0.17} \left(\frac{G}{d}\right)^{0.15} (pd)^{0.25} \tag{6}$$

and [11]

$$U^\pm = 1360 \left(\frac{I^2}{Gd}\right)^{-0.20} \left(\frac{G}{d}\right)^{0.25} (pd)^{0.35}. \tag{7}$$

The comment that the values of the coefficient and the exponents vary pertains fully to the intra-anode section, since the anode unit does not have a second point of contact with the electric arc — a cathode spot. An analysis of the experimental data on the intra-anode voltage drop showed that the values of U_2 are described well by the following equation:

$$U_2 = 715 \left(\frac{I^2}{G_2 d_{\text{n.a.}}}\right)^{-0.13} \left(\frac{G_2}{d_{\text{n.a.}}}\right)^{0.12} (pd_{\text{n.a.}})^{0.25}. \tag{8}$$

The experimental values of the intra-anode voltage drop and the values calculated from Eq. (8) are presented in Fig. 2b.

Section of Open Electric Arc (Fig. 1)

The voltage drop over the section of open electric arc can be determined from the expression

$$U_3 = U_4 + U_5 = \int_0^{l_4} E_4 dl + \int_0^{l_5} E_5 dl. \tag{9}$$

The analytical determination of the dependence of the voltage of an open arc on its length presents great difficulty and complexity in application to practical calculations. Therefore, the voltage drop over the open section of the electric arc was determined from the equation

$$U_3 = U_4 + U_5 = E_{\text{av.}4} l_4 + E_{\text{av.}5} l_5. \tag{10}$$

Let us examine the factors affecting the electric field strength of any section of an open electric arc. For a freely burning arc the electric field strength is practically constant along the length and does not depend on the current strength [10]. For longitudinally ventilated arcs in channels the field strength does not depend on the length of the arc and decreases with an increase in the current strength. This agrees well with the results of the experiments which were conducted. For ventilated arcs the electric field strength depends weakly on the gas flow rate, increasing slightly with its increase [10]. The measurements conducted showed that the current-carrying diameter of the arc increases with an increase in the distance from the nozzle cut to the cross section under consideration, i.e., the degree of compression of the arc decreases. According to the data of the authors of [16], a free arc has a convex upward shape. Since the arc did not bend upward in any of the experiments, one can conclude that it was compressed in all the sections, although the degree of its compression decreased with increasing distance from the nozzle cut. Henceforth we will call such an arc semicompressed. From all that was said above one can conclude that the electric field strength of the open semicompressed arc increases with an increase in the air flow rate and with a decrease in the current strength and current-carrying diameter of the arc.

In deriving the average value of the strength we made the following assumptions: 1) the model of the electric arc is a channel model; 2) LTE exists in the electric arc; 3) the aperture angle 2β of the electric arc does not change with increasing distance from the nozzle cut; 4) the current-carrying diameter of the arc at the exit from the nozzle channel equals the nozzle diameter.

The electric field strength of the arc for the cross section F was approximated by the power-law function

$$E_F = A\,\frac{G^m}{I^n d_F^p}\,. \tag{11}$$

The average electric field strength of the arc over the section from an electrode unit to the point of encounter of the plasma streams was determined from the equation

$$E_{\text{av}} = \frac{AG^m}{2\,I^n}\left(\frac{1}{d_{\text{n}}^p} + \frac{1}{d_{\text{e}}^p}\right). \tag{12}$$

Here the average electric field strength of the open arc over the section from the cathode unit to the point of encounter of the streams equals

$$E_{\text{av.}4} = \frac{AG_1^m}{2I^n}\left(\frac{1}{d_{\text{n.c.}}^p} + \frac{1}{d_{\text{e}}^p}\right). \tag{13}$$

It is seen from Fig. 1 that the current-carrying diameter of the electric arc at the point of encounter of the plasma streams can be determined from the equation

$$d_{\text{e}} = d_{\text{n.c.}} + 2l_4 \operatorname{tg}\beta. \tag{14}$$

Photometry of motion pictures of the electric arc showed that the angle 2β varies slightly as a function of the current strength and air flow rate and lies in the range of $2\beta = 8\text{-}10°$. Accordingly, the angle β is equal to $\beta = 4\text{-}5°$. For such values of the angle $\tan\beta \simeq \beta$. Using the sine theorem one can find the value of l_4. Then Eq. (14) becomes

$$d_{\text{e}} = d_{\text{n.c.}} + 2\beta L\,\frac{\sin\alpha_2}{\sin\gamma} \tag{15}$$

and Eq. (13) takes the form

$$E_{\text{av.}4} = \frac{AG_1^m}{2I^n}\left[\frac{1}{d_{\text{n.c.}}^p} + \frac{1}{\left(d_{\text{n.c.}} + 2\beta L\,\dfrac{\sin\alpha_2}{\sin\gamma}\right)^p}\right]. \tag{16}$$

And for the section from the anode unit to the point of encounter of the streams

$$E_{\text{av}5} = \frac{AG_2^m}{2I^n}\left[\frac{1}{d_{\text{n.c.}}^p} + \frac{1}{\left(d_{\text{n.c.}} + 2\beta L\,\dfrac{\sin\alpha_1}{\sin\gamma}\right)^p}\right]. \tag{17}$$

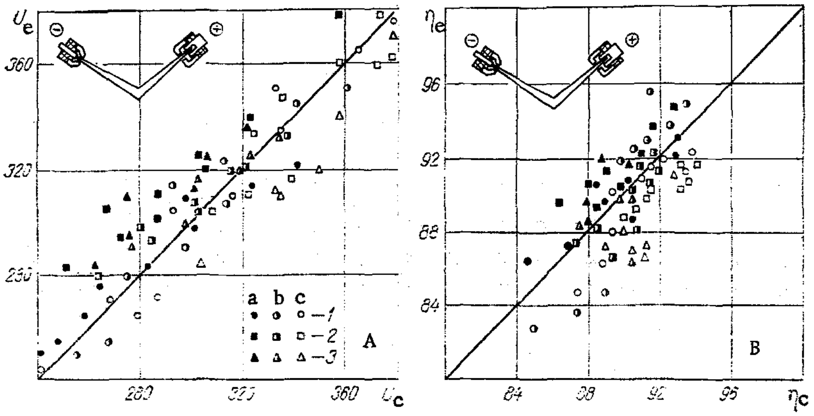

Fig. 3. Comparison of experimental values of voltage of electric arc of two-jet plasmotron (U_e, V) and generalized VAC (U_c, V) (A) and of thermal efficiency (η_e, %) and values calculated from Eq. (23) (η_c, %) (B): 1) $L = 3 \cdot 10^{-2}$ m; 2) $4 \cdot 10^{-2}$; 3) $5 \cdot 10^{-2}$; a) $\alpha = 25°$; b) 40°; c) 55°.

A numerical analysis of the experimental results on the measurement of the potentials and electric field strength of the arc showed that $A = 2460$, $m = 0.1$, $n = 0.15$, and $p = 0.25$.

Then the voltage drops in the cathode and anode sections of the open electric arc of the two-jet plasmotron will equal

$$U_4 = 1230 \frac{G_1^{0.10} L \sin\alpha_2}{I^{0.15} \sin\gamma} \left[\frac{1}{d_{\text{n.c.}}^{0.25}} + \frac{1}{\left(d_{\text{n.c.}} + 2\beta L \frac{\sin\alpha_2}{\sin\gamma} \right)^{0.25}} \right], \tag{18}$$

$$U_5 = 1230 \frac{G_2^{0.10} L \sin\alpha_1}{I^{0.15} \sin\gamma} \left[\frac{1}{d_{\text{n.c.}}^{0.25}} + \frac{1}{\left(d_{\text{n.c.}} + 2\beta L \frac{\sin\alpha_1}{\sin\gamma} \right)^{0.25}} \right], \tag{19}$$

while the overall voltage drop for the entire section of open electric arc is

$$U_3 = 1230 \frac{L}{I^{0.15} \sin\gamma} \left\{ G_1^{0.10} \sin\alpha_2 \left[\frac{1}{d_{\text{n.c.}}^{0.25}} + \frac{1}{\left(d_{\text{n.c.}} + 2\beta L \frac{\sin\alpha_2}{\sin\gamma} \right)^{0.25}} \right] + \right.$$
$$\left. + G_2^{0.10} \sin\alpha_1 \left[\frac{1}{d_{\text{n.c.}}^{0.25}} + \frac{1}{\left(d_{\text{n.c.}} + 2\beta L \frac{\sin\alpha_1}{\sin\gamma} \right)^{0.25}} \right] \right\}. \tag{20}$$

In the case when the angles of inclination of the electrode units are equal ($\alpha_1 = \alpha_2 = \alpha$) Eq. (20) is simplified:

$$U_3 = 615 \frac{L}{I^{0.15} \cos\alpha} \left\{ G_1^{0.10} \left[\frac{1}{d_{\text{n.c.}}^{0.25}} + \frac{1}{(d_{\text{n.c.}} + \beta L \sec\alpha)^{0.25}} \right] + \right.$$
$$\left. + G_2^{0.10} \left[\frac{1}{d_{\text{n.c.}}^{0.25}} + \frac{1}{(d_{\text{n.c.}} + \beta L \sec\alpha)^{0.25}} \right] \right\}. \tag{21}$$

The experimental values of the voltage drop over the section of the open electric arc and those determined from Eqs. (20) and (21) are presented in Fig. 2c.

The total voltage drop over the electric arc of the two-jet plasmotron is determined from Eq. (2), where U_1 is from Eq. (5), U_2 from Eq. (8), and U_3 from Eq. (20) or (21). Numerous tests showed that the experimental values of the VAC of the two-jet plasmotron and those calculated from Eq. (2) agree with an accuracy of ±20%. The experimental values of the VAC of the two-jet plasmatron and those calculated from Eq. (2) are presented in Fig. 3A.

Generalization of Thermal Efficiency

The analytical determination of the thermal efficiency presents a very complicated, almost unsolvable problem because of the impossibility of an exact allowance for all the processes taking place in the plasmatron and the factors affecting them. The efficiency of plasmotrons having an air arc is generalized by the same dimensional complexes as the VAC with the addition of the parametric criterion l/d. The dependence of the thermal efficiency on these complexes is presented in [10] and has the form

$$\frac{1-\eta}{\eta}=A\left(\frac{I^2}{Gd}\right)^m\left(\frac{G}{d}\right)^n(pd)^p\left(\frac{l}{d}\right)^q. \tag{22}$$

However, for the same reasons as for the VAC, it was not possible to generalize the thermal efficiency of a two-jet plasmotron in the form of Eq. (22). To derive the equation for the generalized thermal efficiency of a two-jet plasmatron we use the following argument. In a two-jet plasmotron the useful power is the power released in the open arc and the power going into heating the air in the electrode units. The general equation for the thermal efficiency of a two-jet plasmotron will have the form

$$\eta_0=\frac{U_1\eta_1+U_2\eta_2+U_3}{U_0}. \tag{23}$$

Knowing the voltage drops over all the sections of the electric arc of the two-jet plasmotron and the thermal efficiencies of each electrode unit, one can determine the thermal efficiency of a two-jet plasmotron.

An analysis of the results of the calorimetry of the water cooling the electrode units showed that the thermal efficiency of the cathode unit is described by the expression

$$\frac{1-\eta_1}{\eta_1}=6.3\cdot10^{-7}\left(\frac{I^2}{G_1d_{\text{n.c.}}}\right)^{0.40}\left(\frac{G_1}{d_{\text{n.c.}}}\right)^{-0.27}(pd_{\text{n.c.}})^{0.30}\left(\frac{l_{\text{n.c.}}}{d_{\text{n.c.}}}\right)^{0,50}. \tag{24}$$

The greater dependence of the thermal efficiency η_1 of the cathode unit on the current strength than in [11] is explained by the absence of an anode spot in the electrode unit.

The thermal efficiency η_2 of the anode unit is described by the following expression:

$$\frac{1-\eta_2}{\eta_2}=2.16\cdot10^{-5}\left(\frac{I^2}{G_2d_{\text{n.a.}}}\right)^{0.27}\left(\frac{G_2}{d_{\text{n.a.}}}\right)^{-0.27}(pd_{\text{n.a.}})^{0.30}\left(\frac{l_\text{a}}{d_\text{a}}+\frac{l_{\text{n.a.}}}{d_{\text{n.a.}}}\right)^{0.50}. \tag{25}$$

In the studies conducted the parametric criterion $l_{\text{n.c.}}/d_{\text{n.c.}}$ varied in the range of (0.75-3.75), $l_{\text{n.a.}}/d_{\text{n.a.}}$ in the range of (0.8-4.0), and l_a/d_a in the range of (2.0-6.0).

By substituting the values of the thermal efficiencies of the electrode units determined from Eqs. (24) and (25) into Eq. (23) [the values of U_3, U_1, U_2, and U_0 are determined from Eqs. (20), (5), (8), and (2), respectively], one can determine the thermal efficiency of a two-jet plasmotron with an accuracy of ±10%.

The experimental values of the thermal efficiency and the values determined from Eq. (23) are presented in Fig. 3B.

NOTATION

L, line of centers, distance between nozzle cuts of electrode units, m; α, angle between axis of an electrode unit and line of centers; γ, sum of angles of inclination of electrode units ($\gamma=\alpha_1+\alpha_2$); 2β, aperture angle of semicompressed electric arc; I, current strength of arc, A; U, voltage drop, V; G, flow rate of plasma-forming gas, kg/sec; d, diameter of channel, m; l, length of channel, m; E, electric field strength of arc, V/m; σ_0, h_0, controlling values of specific electrical conductivity and specific enthalpy; η, thermal efficiency. Indices: 0, two-jet plasmotron; 1, cathode unit; 2, anode unit; 3, entire section of open electric arc; 4, section of open electric arc from cathode unit to point of encounter of plasma streams; 5, section of open electric arc from anode unit to point of encounter of plasma streams; av, average value; n.c., nozzle of cathode unit; a, anode; n.a., nozzle of anode unit; e, point of encounter of plasma streams.

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SOME PROBLEMS OF CONVECTIVE DIFFUSION TO A SPHERICAL PARTICLE WITH Pe ≤ 1000

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The problem of convective heat and mass exchange during the slow motion of a single drop in a uniform and a shear stream, as well as during the motion of a gas bubble in a power-law liquid, is solved using finite-difference methods.

The determination of the intensity of external heat and mass exchange of a spherical particle under the conditions of axisymmetric streamline flow is connected with the solution of the equation of convective diffusion

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial C}{\partial r}\right)+\frac{1}{r^2\sin\Theta}\frac{\partial}{\partial\Theta}\left(\sin\Theta\frac{\partial C}{\partial\Theta}\right)-\frac{\mathrm{Pe}}{2}\left(V_r\frac{\partial C}{\partial r}+\frac{V_\Theta}{r}\frac{\partial C}{\partial\Theta}\right)=0 \tag{1}$$

with the following boundary conditions:

$$C|_{r=1}=1;\quad C|_{r\to\infty}=0. \tag{2}$$

In Eq. (1) the components V_r and V_Θ of the liquid velocity are expressed through the stream function by the equations

$$V_r=-\frac{1}{r^2\sin\Theta}\frac{\partial\Psi}{\partial\Theta};\quad V_\Theta=\frac{1}{r\sin\Theta}\frac{\partial\Psi}{\partial r}.$$

In the present report Eq. (1) is analyzed for several model flows pertaining to cases of slow streamline flow over a particle. Since the Schmidt numbers for real liquids have the order of 10^3, the values of the Peclet number lie in the range of $1 \leq \mathrm{Pe} \leq 1000$ even for small Reynolds numbers ($\mathrm{Re} \leqslant 1$).

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