16. B. A. Koval'chuk, "Experimental study of heat capacity of argon over a wide range of state parameters including the critical point," Candidate's Dissertation, Moscow (1977).
17. M. A. Anisimov, B. A. Koval'chuk, V. A. Rabinovich, and V. A. Smirnov, Thermophysical Properties of Substances and Materials. Physical Constants and Properties of Matter, 3th edn. [in Russian], Moscow (1974), pp. 237-245.
18. A. V. Voronel', V. G. Gorbunova, V. A. Smirnov, et al., Zh. Éksp. Teor. Fiz., 63, No. 3, 964-980 (1972).
19. Sh. P. Adamov, M. A. Anisimov, S. B. Kiselev, V. A. Rabinovich, and V. A. Smirnov, Teplofiz. Vys. Temp., 18, No. 5, 1115 (1980).
20. J. Thoen, E. Vangeel, and E. W. Van Dael, Physica, 45, No. 3, 339-356 (1969).
21. J. Thoen, E. Vangeel, and E. W. Van Dael, Physica, 52, No. 2, 205-224 (1971).
22. I. I. Novikov and Yu. S. Trelin, Teploénergetika, No. 2, 79-85 (1962).
23. S. L. Rivkin and V. M. Gukov, Teploénergetika, No. 10, 82-83 (1971).
24. Sh. P. Adamov, B. A. Koval'chuk, and V. A. Smirnov, Tr. VNIIFRTI, No. 32, 76-85 (1977).
25. I. M. H. Levelt-Sengers, J. Ind. Engin. Chem. Fundam., 9, No. 3, 470-479 (1970).
26. J. C. Albright, J. J. Edwards, Z. J. Chen, and J. V. Sengers, J. Chem. Phys., 87, No. 3, 1717-1725 (1987).
27. Kh. I. Amirkhanov, N. G. Polikhronidi, and R. G. Batyrova, Teploénergetika, No. 3, 70-72 (1970).
28. Kh. I. Amirkhanov, N. G. Polikhronidi, B. G. Alibekov, and R. G. Batyrova, Teploénergetika, No. 12, 59-62 (1971).
29. V. V. Altunin, Thermophysical Properties of Carbon Dioxide [in Russian], Moscow (1975).

A TRANSVERSELY BLOWN ARC DISCHARGE IN A PLASMATRON WITH COAXIAL ELECTRODES

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A discharge is investigated of an alternating current in a plasmatron with "hot" coal graphite electrodes, the faces of which are located in one plane. Experiments are described with a segmented external electrode. On the basis of an analysis of the oscillograms of current in the electrode segments and of photographs of the front part of the plasma tip it is concluded that the burning of the discharge cannot be in the form of a solitary arc and that the discharge is comprised of a system of arcs. Calculation of the volt–ampere characteristics of the transversely blown off diffuse discharge showed the impossibility of its burning in the conditions under consideration.

In a series of industrial electric arc devices, the discharge takes the form of a system of parallel arcs operating from one voltage source [1-3]. In [4] the questions of the analysis, modeling, and synthesis of multi-arc systems are examined for the first time. It is observed that on a smooth cylindrical electrode a stationary division of the arc was not achieved experimentally. Segmentation of the discharge in [4] is achieved by embedding thermo-emissive inserts into the body of the electrode. It is shown that stable burning of the radial elements of the segmented discharge is guaranteed by their rising volt–ampere characteristics, but the cause of the division of the discharge is the radial flux of the gas jet toward the walls of the electrode.

In the present work a discharge in a plasmatron with "hot" electrodes [5] is investigated. Experimental observation of the operation of the device allows one to propose that in

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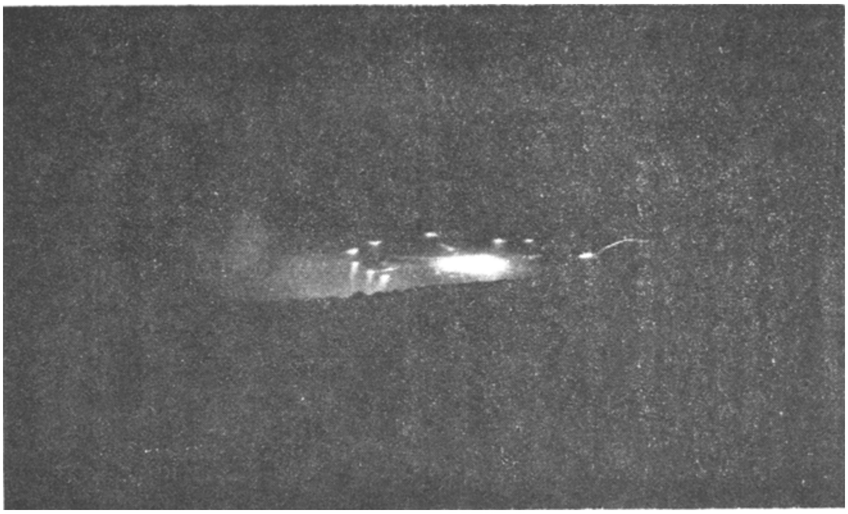

Fig. 1. Base spots on the face of the external electrode of a plasmatron.

a plasmatron with coaxial open coal graphite electrodes, an arc discharge may be represented as a system of simultaneous hot arcs. Photographing the front faces of the electrodes about one minute after the ignition of the discharge showed that when the strength of the current is of the order of 1500 A on the front face of the exterior electrode there are ~20 regularly distributed, slowly moving base spots with a diameter of 3-5 mm. On the face of the interior core electrode the base spots of the discharge visually fuse into a single spot with dimensions on the order of 20 mm. A photograph definitely fixing the presence of the indicated base spots on the exterior electrode is shown in Fig. 1.

The goal of the present work is to show that the observed discharge [5] is actually a system of fan-shaped (radially) distributed arcs, but the observed base spots correspond to their near electrode regions. Competing hypotheses of a single powerful electric arc, rapidly moving upon the circular face of the electrode, and about a homogeneous (diffuse) discharge are tested.

ELECTRICAL MEASUREMENTS

Rapid photography (a shutter speed of 1/500 sec) and movie photography (3000 frames/sec) allowed one to determine only the quantity, position, and dimension of the base spots. To pass beyond the arcs themselves (or an arc itself) failed due to the brilliant radiance of the hot electrodes' surface and to the extended circumferential part of the jet with a temperature on the order of 4-5 kK.

Special experiments were made for the determination of the character of the arc discharge. Their substance is explained by Fig. 2, in which is shown the face segments of the graphite electrodes. The outer electrode (insert) was partially slotted into four plasmatron sections, electrically connected in the holder. The slots between sections were filled up with non-conducting materials (ceramics), in order to avoid disturbances in the gas dynamics of the flux at the plasma tip. From each section, starting from 120 mm, readings of the

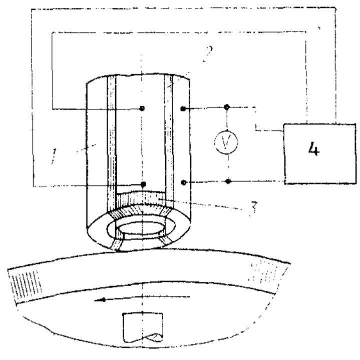

Fig. 2. Schematic of the experimental device: 1) ring or annular electrode; 2) slot; 3) ceramic insert; 4) oscillograph of type H117.

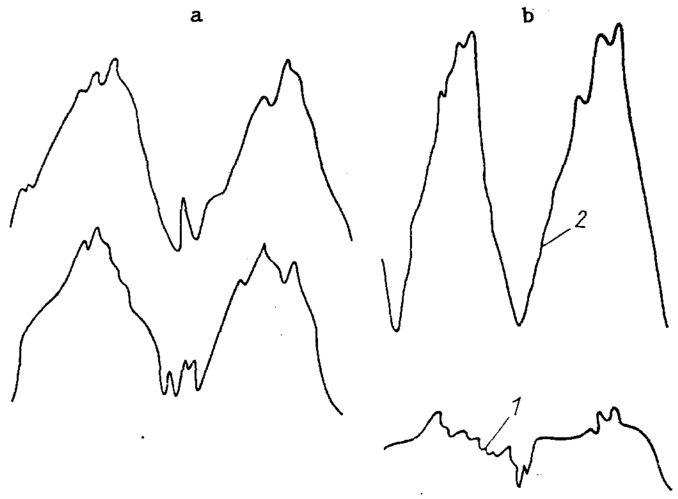

Fig. 3. Oscillograms of the current in segments of an external electrode: a) with two "non-suppressed" segments; b) with a "suppressed" 1 and "non-suppressed" 2 ceramic insert segment.

voltage drop resulting from the resistance of the graphite were taken and fed without additional amplification into the input of a galvanometer oscillograph of the type H117. The frequency response pass band of the galvanometer extended to 15 kHz.

The dimensions of the tip of the plasmatron were as follows: outer diameter — 0.12 m; inner diameter — 0.08 m; and slot length — 0.15 m. The operating regime of the plasmatron had a voltage of 80 V and a current of 1400 A. The consumption of plasma forming gas, air, was $\sim 1.5 \cdot 10^{-3}$ kg/sec. The distance to the target (a cement ring) was 20 mm. The speed of the ring was ~0.3 m/sec.

A comparative analysis of the oscillograms, obtained for any pair of segments at different moments in time (Fig. 3a), shows that in all segments in the course of any half period of the assigned source, an approximately identical current flows without delay. Such a picture is possible in only three cases:

a) the discharge is a stable system from four or more arcs;

b) the discharge takes the form of a single rapidly shifting arc, making contact for a time shorter than the time resolution of the measuring device;

c) the discharge is homogeneous (diffuse).

The second assumption in the present case seems least likely, since it leads to the estimate that the value of the velocity of migration of the near electrode segments of the arc is $v \geq 500$ m/sec.

We note that for the purpose of estimating the influence of "directed" potential upon each segment a control experiment was conducted in which one of the segments was slotted a small amount (~20 mm) and was augmented with an equivalent thickness of isolating ceramic insert, which precluded heating of the arc on the indicated segment. Relative oscillograms for "suppressed" and for an arbitrary other segments are shown in Fig. 3b, from which one may see that the conclusions made in above experiment remain correct.

The effective voltage drop in all experiments with operating segments was near 0.2 V, which agreed with an estimate of the voltage drop for the known specific resistivity of graphite $\rho_0 \simeq 8 \cdot 10^{-6}$ Ohm·m.

VOLT—AMPERE CHARACTERISTIC (VAC) OF A DIFFUSE DISCHARGE

A comparison of the actual working regime of a plasmatron with the VAC of a uniform diffuse discharge allows one to make further conclusions.

For a qualitative estimate of the VAC of a diffuse discharge, we remark that in the present condition we may restrict ourselves to a simplified model approach in virtue of the simple geometry. The discharge uniformly spans the interelectrode space (see Fig. 2) and taking into account its blow off by gas and its limitation by the obstruction that is being

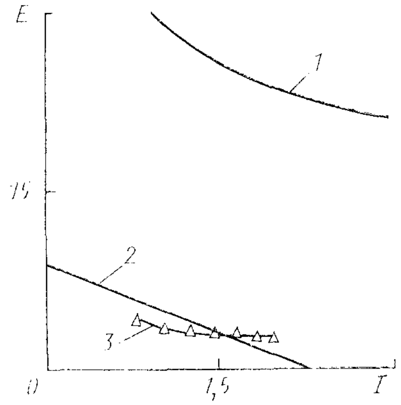

Fig. 4. A comparison of the calculated VAC of a diffuse discharge with the experimental values: 1) calculated according to formula (4); 2) on the load line of the voltage source; 3) experimental VAC [5]. The field E is in kV/m and the current I is kA.

processed, it may be considered practically one dimensional. Then one may assume that the gradients of all properties of the plasma in the transverse (in relation to the gas flux) direction are equal to zero. In this case the principal energy losses are connected with the removal of the working gas. Therefore, for a description of the stationary spatial temperature distribution we restrict ourselves to a one-dimensional equation of thermal conductivity with piecewise constant coefficients, simulating a strong linear dependence of the properties of the gas upon temperature and the influence of geometry of the superimposed electric field:

$$\frac{d^2T}{dx^2} + \frac{G}{\rho\chi}\frac{dT}{dx} + \frac{I^2}{\lambda\sigma d^2 L^2}\Theta(x)\Theta(T - T_g) = 0. \tag{1}$$

The first and second components correspond to the thermal conductivity and convective heat loss. The third component reflects the degree of heating by the current of the region with transverse area L × d, where d is the effective transverse dimension of a segment of the discharge (perimeter of the inter-electrode ring region); and L is the dimension of the conducting region along the flux or flow. The presence of a multiplier in the form of a step function $\Theta(T - T_g)$ corresponds to a jump in the conductivity of the gas σ from practically zero at relatively low temperatures to $\sigma = 5 \cdot 10^3$ $(\mathrm{Ohm \cdot m})^{-1}$ for $T \geq T_g \approx 7$ kK [6, 7]. In virtue of the weak dependence of ρχ and λ upon the density of the gas and upon the temperature in typical arc discharge region parameters with T = 7-15 kK at atmospheric pressure, for estimates one may restrict oneself to the use of average constant quantities. In accordance with [8] in what follows it is assumed that $\rho\chi \approx 1.6 \cdot 10^{-4}$ kg/(m·sec), and λ is ≈1 W/(m·K).

We emphasize that the necessary condition for finding a solution to the problem which is spatially limited to the current distribution is provided by the factor θ(x), which corresponds physically to a stabilization of the transverse blown-off discharge by the electrodes themselves and by the target.

A solution of Eq. (1) which with its first derivative is unique and continuous, takes the form (for λ = const):

$$T(x) = \begin{cases} \dfrac{\rho\chi I^2}{G\lambda\sigma d^2 L}, & x \leqslant 0, \\ \dfrac{\rho^2\chi^2 I^2}{G^2\lambda\sigma d^2 L^2}\left[1 - \dfrac{G(x - L)}{\rho\chi} - \exp\left(-\dfrac{Gx}{\rho\chi}\right)\right], & 0 \leqslant x \leqslant L, \\ T_g \exp\left(-\dfrac{G(x - L)}{\rho\chi}\right), & x \geqslant L \end{cases} \tag{2}$$

for the condition

$$T_g = \frac{\rho^2\chi^2 I^2}{G^2\lambda\sigma d^2 L^2}\left[1 - \exp\left(-\frac{GL}{\rho\chi}\right)\right]. \tag{3}$$

The solution of Eq. (3) for the given consumption rate G, transverse dimension d, and current strength I allows us to find the dimension L of the discharge along the gas flow, and subsequently also the maximum temperature at the exit of the discharge:

$$T_m = \frac{\rho\chi I^2}{G\lambda\sigma d^2 L}.$$

The use of Ohm's Law in the form $I = dL\sigma E$, where E is the intensity of the external electric field, together with the condition (3) gives the volt-ampere characteristics of a diffuse discharge:

$$I = d\sqrt{\sigma\lambda T_g}\frac{E}{E_{\min}}\ln\left(\frac{1}{1-E_{\min}^2/E^2}\right),$$
$$E_{\min} = \frac{G}{\rho\chi}\sqrt{\frac{\lambda T_g}{\sigma}}. \qquad (4)$$

Calculations based on (4) for the actual regime of operation of a plasmatron [5] with d = 0.2 m and G = 2.8 kg/m²·sec for comparable levels of current (Fig. 4) give a value of E which is more than an order of magnitude larger than values in the experiment. The remoteness of the calculated VAC, and likewise the absence of its intersection with the load line of the source indicate the principal impossibility of the occurrence of a diffuse discharge for the device [5]. This circumstance narrows the circle of physical explanations of the operating regime of the discharge under investigation.

Thus, the facts presented show that in a plasmatron with "hot" electrodes the observed discharge is in the form of a system of parallel arcs. The spatial regularity of a multi-arc discharge is achieved due to the specific geometry of the tip of the plasmatron and to the forced blow off of the discharge by the transverse flow of the gas. The organization of the burning of the discharge in the form of a system of arcs allows one to increase the operating lifetime of a plasmatron generator, to increase the width of a plasmatron jet and in the final analysis to increase the output of a plasma device for heating of the surface of objects.

NOTATION

I, discharge current; λ, thermal conductivity coefficient; σ, conductivity; ρ, density; χ, thermal diffusivity; T, temperature; x, coordinate; G, gas consumption across a unit area; $\Theta(x)$, theta step function; T_g, temperature of an abrupt increase in the plasma conductivity; $E_{\min}$, minimum value of the field strength in a stable discharge.

LITERATURE CITED

1. O. B. Bron, Electric Arcs in Control Apparatus [Russian translation], Moscow–Leningrad (1954).
2. V. V. Azharonok, V. A. Gubkevich, A. I. Zolotovskii, et al., Inzh.-Fiz. Zh., 50, No. 3, 362-367 (1986).
3. G. A. Sisoyan, The Electric Arc in an Electric Furnace [in Russian], Moscow (1974).
4. O. Ya. Novikov, P. I. Tamkivi, A. N. Timoshevskii, et al., Multi-Arc Systems, Novosibirsk (1988).
5. N. V. Pashatskii and A. N. Goncharov, Bulletin of the Siberian Branch of the Academy of Sciences, Technical Physics Series, No. 16, 3rd edn. (1984), pp. 83-86.
6. M. F. Zhukov and A. S. Koroteev (eds.), The Theory of the Thermal Electric Arc Plasma [in Russian], Vols. 1 and 2, Novosibirsk (1987).
7. V. Finkel'nberg and G. Mekker, Electric Arcs and Thermal Plasma [in Russian], Moscow (1961).
8. N. B. Vargaftik, Handbook of Thermophysical Properties of Gases and Liquids [in Russian], Moscow (1963).