POTENTIAL DISTRIBUTION ALONG THE ARC IN A VORTEX-STABILIZED PLASMA GENERATOR

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Published research on the potential distribution along an arc and the effect of arc length on the current-voltage characteristics are mainly devoted to open arcs [1], cylindrical arcs [2, 3], and arcs in a laminar flow with low gas flow rates [4]. Rotating probes have been used successfully to determine the potential distribution in open arcs [1]. Great technical difficulties are involved in the application of moving probes to cylindrical arcs and arcs in laminar flows burning in ducts. Such arcs usually almost completely fill the stabilizing duct, which consists of ring segments insulated from each other. At high resistances in the external circuit, these segments can be used as probes to determine the potential distribution along the arc. Probes have also been used in attempts to determine the potential distribution along stabilized arcs [5].

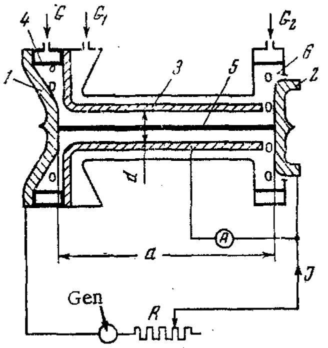

Fig. 1. Diagram of plasma generator: 1) cathode; 2) anode; 3) tube; 4) swirl ring; 5) arc; 6) counter-pressure chamber; Generator; G, G_1, G_2— air supply.

In the powerful plasma generators used in industrial and high-temperature research, the stabilized arc burns in a turbulent gas flow, and there may be an appreciable layer of cold gas in the space between the duct and the arc column. The potential drop across this layer may be large. In this case, if connected to one of the electrodes across high resistances, the segments operate not like ordinary probes but like the electrodes of a semi-self-sustained discharge between the column and the duct wall across the layer of cold gas. We know of no published research on the determination of potential distribution in plasma generators under such conditions.

In some cases a qualitative description of the potential distribution along an arc burning in a gas flow may be based on data obtained by varying the interelectrode gap [6]. In [6], however, according to the author's data, the arc was unstabilized, and its length was considerably greater than the distance between the electrodes.

The present work is devoted to the determination of the voltage of a stabilized arc by varying its length in a turbulent flow (in the experiments the Reynolds number at the duct inlet, determined from the mean axial velocity of the cold gas, varied between 2.7×10^4 and 8.1×10^4). The potential distribution was determined from the voltage data, and also measured directly with electrostatic voltmeters.

Experimental. Figure 1 shows a plasma generator for investigating the influence of the arc length and gas flowrate on the (U, I) characteristics (U is the voltage and I the current of the arc). Its basic features are a copper cathode 1 and anode 2, both water-cooled, with flat ends, and a cylindrical air-cooled copper tube 3. Air is delivered to the arc chamber through four tangential 3 mm diameter apertures in the swirl ring 4 at a distance of 2.5×10^{-2} m from the chamber axis. To check the stability of the position of the arc 5 tests were performed in which the channel 3 was replaced by a quartz tube. The tests showed that within the range in which the parameters in our experiments were varied the arc is located with sufficient stability along the tube axis.

The arc length was varied by varying the length of tube 3. The absence of arc shunting across the tube 3 was checked by an ammeter A. In all the experiments the distance between the anode 2 and tube 3 was kept at 5 mm, the minimum clearance between the cathode 1 and the tube 3 was 2.8 mm, while the inlet of the tube 3 had a radius of curvature of 8 mm.

If the arc length is reduced at constant values of the current and flowrate G, its power decreases. This leads to a reduction of the pressure in the arc burning zone as compared with the long arc. Therefore, to regulate the pressure independently of the arc length, a counterpressure chamber 6 was used. Air was delivered to this chamber and, by varying the flowrate G_2, it was possible to regulate the pressure in the burning zone. Preliminary recordings were made of the dependence of the pressure p at the cylindrical wall of the swirl chamber on G and I at the maximum arc length (with discharge to the atmosphere). In subsequent experiments the same pressure was maintained as for maximum arc length with the same values of G and I, while the gas flowed out of the arc chamber through the clearance between the anode 2 and counterpressure chamber 6. U and I were measured with class-1.5 N-375 instruments, the potential of the segments by class-1.5, C-50 and C-95 electrostatic voltmeters, air flowrate by type RS-7 and RS-5 rotameters, and p_k by a standard class-0.35 type MO manometer.

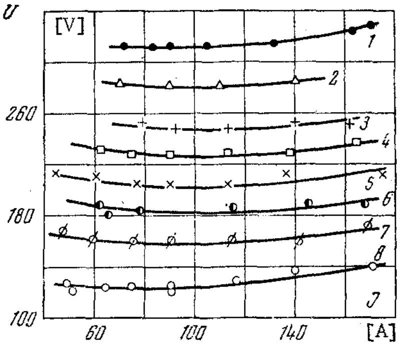

Fig. 2. Arc voltage as a function of current. Curves 1–8 obtained for *a* = 136, 123, 111, 100, 89, 77, 64.5 and 51.5 mm, respectively with G = 8 g · $\sec^{-1}$.

Arc characteristics. Figure 2 gives the (U, I) characteristics for different interelectrode gaps. A noticeable feature is the absence of steep drops. Starting at a current of about 100 *a* they begin to rise. This confirms the conclusion of [7] that one of the main reasons for the formation of drooping (U, I) characteristics in plasma generators in the above range of parameter variation is the reduction of arc length as the current increases. The characteristics for flowrates of 4, 6, 10, and 12 g · $\sec^{-1}$ are analogous to those reproduced in Fig. 2 and are therefore not given here.

Figure 3 shows the arc voltage as a function of arc length for a current of 90 *a*; U is seen to depend linearly on *a* and very slightly on G. The relations for other currents and flowrates in the range I = 60–170 a, G = 4–12 g • $\sec^{-1}$ do not differ qualitatively from those given. In ordinary swirl-type plasma generators with shunting and the above parameter variation, the increase in U as G increases is therefore a result mainly of elongation of the arc. In our case the weak dependence of U on G can be explained by the fact that most of the gas passes along the tube walls at a considerable distance from the arc, without particularly influencing the phenomena in the arc column.

For a constant Knudsen number, the arc characteristics for the type of plasma generator investigated can be generalized in the form [7]

$$U = \frac{I}{d} f_1(a/d,\ G/d,\ I^2/Gd). \qquad (1)$$

For d = const, taking into account the linear variation of U as a function of *a*,

$$U = c + af(I,\ G,\ I^2/G). \qquad (2)$$

It can be seen from the experimental results (e.g., Fig. 3) that for the given variation of the parameters a constant value of 20 V can be taken for c. The function f can be expanded as a series in I

$$f = \psi_0(G) + \psi_1(G)\, I + \psi_2(G)\, I^2 + \ldots.$$

The similarity of the shapes of the (U, I) characteristics for different values of G suggests simplifying f as

$$f = \psi(G)(c_0 + c_1 I + c_2 I^2).$$

Within a narrow range of variation of G, ψ, G, can be taken as a power. The empirical formula then obtained takes the form

$$U = 20 + aG^{0.15}(5160 - 14.8I + 0.073I^2), \qquad (3)$$

where U is in volts, *a* in meters, G in kg • $\sec^{-1}$, I in *a*, with 50 *a* < I < 170 *a*, and 0.004 < G < 0.012. The distance from the cathode was 0.04–0.13 m, and d was 0.0104 m. The maximum deviation of the experimental results from (3) was close to the maximum measuring error.

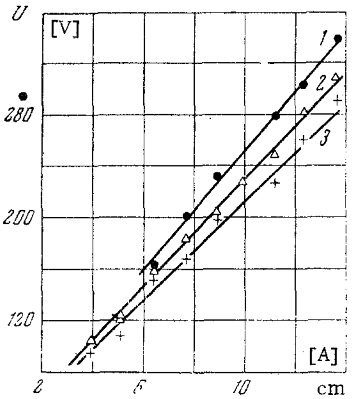

Fig. 3. Arc voltage as a function of arc length for I = 90 *a*, d = 10.4 mm; curve 1) G = 12.8 g • $\sec^{-1}$, curve 2) G = 8 g • $\sec^{-1}$.

Potential distribution along arc. The use of a counterpressure chamber 6 in the experiments to determine the potential by the method of arc length variation (Fig. 1) permitted the pressure distribution in the burning zone to be kept constant when the tube 3 was shortened. The conditions of arc burning in the section between the end of the tube and the anode are extremely complicated and different from the conditions in the tube. Directly at the anode we get complex flow of the heated swirled stream and the behavior of the anode potential drop region under these conditions is not known. Accordingly, it is still difficult to make any theoretical estimate of the magnitude of the potential drop over this section. Therefore the arc potential UU° relative to the anode at the end of the tube (at a distance of 4.5 mm from the anode) was determined by means of a rotating probe [1].

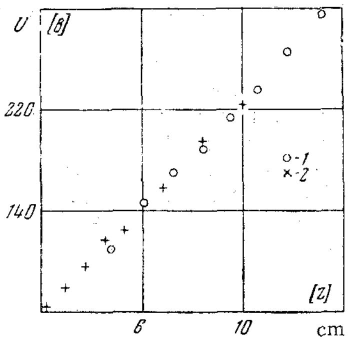

Fig. 4. Potential distribution along arc with G = 8 g $\sec^{-1}$, I = 75 a, d = 10.4 mm, cathode at zero potential. 1) Method of arc-length variation; 2) electrostatic method; Z is the distance to the cathode.

Analysis of oscillograms of the probe characteristic showed that in the absence of shunting between the arc and the duct 3 the potential at the probe measuring point B changes slightly as the interelectrode gap is varied. For the given values of G, I, and *a* it remains within the limits −14 ± 4 V. (In this case the error due to the contact potential difference around the probe is not taken into consideration.) The quantity $U^+ = U + U^\circ$ is the potential of point B relative to the cathode. The potential distribution determined by this method is given in Fig. 4. Neglecting this slight dependence of U° on the interelectrode gap, we obtain from (3) an approximate formula for the field strength in the arc column

$$E = -G^{0.15}(5160 - 14.8I + 0.073I^2)\ \mathrm{V \cdot m^{-1}}. \qquad (4)$$

For the experimental conditions E is within the limits 1900–2500 V • m^{-1}. The potential distribution was also measured by measuring the potentials of the insulated segments of the tube 3. These results are also given in Fig. 4. Both methods are suitable for potential determination. The segment potentials were also measured by passing a semi-self-sustained discharge current of the order of 10 *a* through them. The results of such measurements for the end section of the arc, where the discharge voltage at small currents is relatively low, were in agreement with the results of measurements by the above methods. For the initial segments at currents of the order of 10^{-5} a, the last method gives a rather high value of the potential, since there is a certain rise over the section of the semi-self-sustained discharge across the gas layer (in this instance the polarity of the potential is taken into consideration).

Calorimetric analysis showed that the heat losses across tube 3 were small (the thermal efficiency of the positive column is of the order of 90%), and therefore the mean-mass gas-temperature rises as one moves along the channel. A linear potential distribution is thus not a sufficient condition of constancy of the temperature profile along the channel. Such a potential distribution can be explained by reconstruction of the temperature profile along the channel and by the change in the composition of the air downstream as a result of chemical reactions and dissociation. The weak dependence of the potential distribution on gas flowrate is explained by the fact that over the lengths investigated only a small proportion of the gas is subjected to the direct influence of the arc. As the length is increased and a greater and greater proportion of the gas is heated, the potential distribution may differ considerably for different flowrates. Finally, at very great lengths, the power of unit length of arc is equal to the heat loss through unit length of duct, and the subsequent growth of potential is again linear [8]. However, for the same currents and duct diameters the electric field strength in a cylindrical arc when there is no flow must differ from that in a turbulent flow because of the mixing of the gas.

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