ROTATION OF ELECTRODE SEGMENTS AND PROPERTIES OF AN ARC COLUMN IN A PLASMA GENERATOR WITH VORTEX GAS STABILIZATION

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This article gives the results of an investigation of the motion of the electrode segments of an arc over the inner surface of the electrode under the action of the circumferential velocity component of the vortex gas flow in a dc plasma generator with vortex stabilization, and examines the spatial distribution of the arc column. A SKS-1M high-speed motion-picture and a SFR-1M time magnifer were used to study the operation of a two-chamber plasma generator and a plasma generator with fixed arc length (with an intermediate transparent tube) in the current range I = 50–150 a. The circumferential velocity of the gas and radial segments of the arc in the inner electrode of a two-chamber plasma generator and the current density in the arc spots and in the column are found.

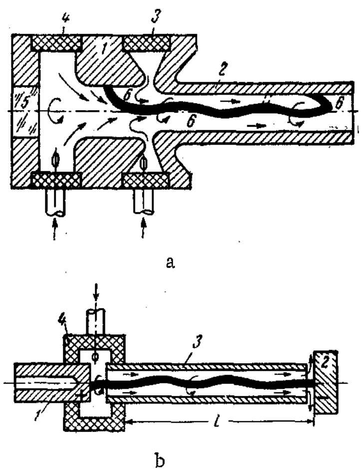


Fig. 1

Forced displacement of the arc spot is now used in many plasma generators; this is done with a view to reducing the erosion of electrode material. When using aerodynamic forces to displace the arc, one must know the difference between the velocity of the arc spot and that the of the gas stream, how uniformly the arc spot moves over the electrode surface, and the current density in the arc spot. This information is needed to perform thermal calculations for the electrodes.

1. The experimental apparatus is is shown schematically in Fig. 1. The plasma generator depicted in Fig. 1a has two water-cooled hollow cylindrical electrodes—an inner electrode 1 and outer electrode 2; 3, and 4 are swirl chambers made of insulating material, and 5 is a transparent wall made of heat-resistant glass, through which photographs may be taken. The diameter of the outer electrode is 10 mm, that of the inner one 15 mm, and the diameter of the swirl chambers is 50 mm. Giving the inner electrode a diameter somewhat larger than that of the outer electrode makes it possible to get a clear projection of the arc region adjacent to the surface of the inner electrode on the relatively dark background of the inner end of the outer electrode, and to avoid a superposed image of the arc spot on the outer electrode. The main part of the positive column lies near the axis of the electrodes in the minimum-pressure zone. The arc is closed at the electrode wall by radial segments which rotate due to the effect of the swirled gas flow.

The gas was supplied through two swirl chambers which fixed the rotation zone of the end of the arc 6 at the middle of the cylindrical section of the inner electrode. In other respects, the principle of operation of the plasma generator is almost the same as that described in [1, 2].

In the generator shown in Fig. 1b, which has a fixed arc length, massive copper uncooled electrodes 1 and 2 are located at either end of a transparent quartz tube 3, 22 mm in diameter and 500 mm long. Air is sent through a swirl chamber 4 situated close to the first electrode.

The photographic system for Fig. 1a is illustrated in Fig. 2. Photography was restricted in all cases to the steady-state arc burning regime 10–15 sec after ignition. To reduce the luminescent gas background, a combination of ZhS-17 and C3C-22 light filters was used.

2. Typical photographs of the arc from the side of the inner electrode obtained at speeds of $5 \cdot 10^3$ frames/sec (SKS-1M) and $125 \cdot 10^3$ frames/sec (SFR-1M) are shown in Figs. 3 a, b. Figure 3a shows (see diagram 3c) the radial arc segment in the inner electrode in the initial position 1 and the final position 2 due to displacement during the frame exposure time, the radial segment of the arc in the outer electrode 3, the projection of the arc column 4, and the bright outlines of the internal cavities of the electrodes: the inner-5 and outer-6. In Fig. 3b the end of the arc in the outer electrode is not visible due to the small field depth of the time magnifier.

It is clear from the photographs that the radial segments of the arc in the inner and outer electrodes are in the shape of a comma convex in the direction of motion of the gas. Examining Fig. 3b in detail (see explanatory diagram 3d), one notes the characteristic constriction of the arc column at the maximum radius on the electrode; this constriction is roughly the same for different polarities. The ratio of the diameter of the constricted part (arc spot on the electrode) to the column diameter near the spot (section 1–1) is, on the average, 0.78 and varies only slightly at currents in the range 50–150 a and pressures of 2 to 5 bar.

3. Experiments revealed a difference in the motion of the electrode segment of the arc and the spot in the inner electrode when the pressure in the rotation zone changes from 2 to 6 bar. At reduced pressure (about 2 bar) electric breakdown from the radial segment of the column to the electrode wall is often observed to occur as a result of jumping of the spot over the electrode (shunting). Figure 4 shows the radial arc segment in the presence of such a breakdown, the new (short on the photograph) channel being formed down stream with respect to arc motion. Jumping (due to breakdown) was observed in the experiments only for an anode spot, when the electric field in the arc-electrode gap causes electrons emitted by the arc to strike the wall of the electrodes.

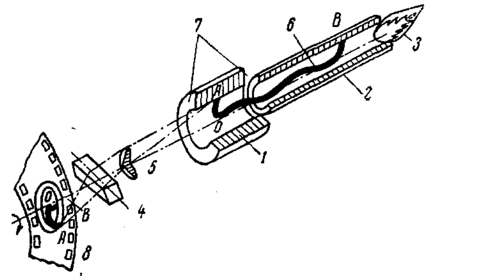
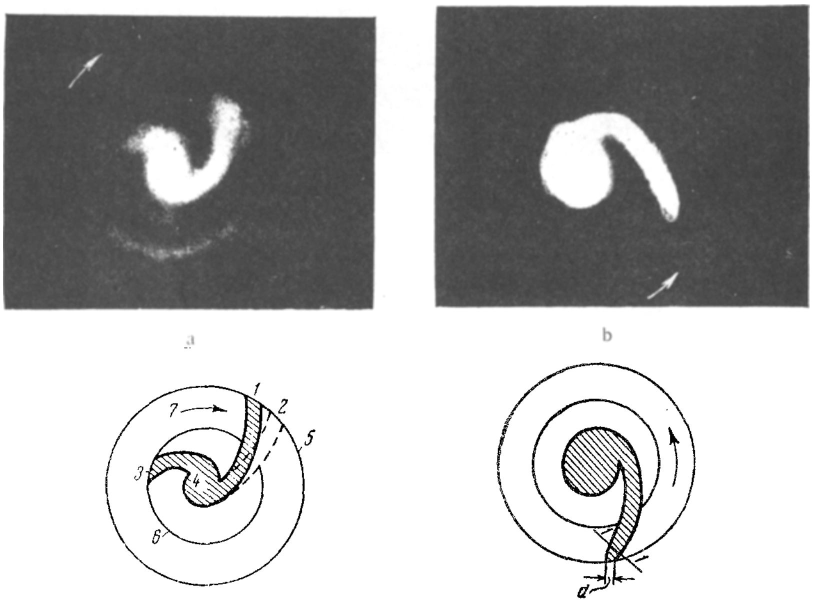


Fig. 2

An estimate of the electric field strength in the breakdown gap from measurements with a potential probe made by the authors, together with A. D. Lebedev, gives a value of the order of 100 V per cm. In the case of a cathode spot, it is difficult for breakdown to occur, since the cold cathode emission is not enough at the given intensity for breakdown. In this case breakdown was not in fact observed in our experiments.



c Fig. 3 d

With increase in pressure and a corresponding increase in breakdown voltage, according to the right branch of the Paschen curve, breakdown did not occur, even in the case of an anode spot, and the spot motion was continuous in all cases. The motion of the radial segment of the arc and the spot at a pressure of 5 bar is analyzed in Fig. 5 for an anode. It is clear from the photograph, which gives almost a complete picture of the rotation of the arc, that the arc moves quite uniformly during one period of rotation. When the pressure is decreased, there is a characteristic increase in the nonuniformity of spot motion over the electrode, in addition to the appearance of breakdowns over the anode segment of the arc.

4. The photograph in Fig. 3b shows that the projection of the portion of the arc near the axis has a diameter much greater than the diameter of the column in the radial segment. This may be explained in relation to the behavior of the arc column in the outer electrode.

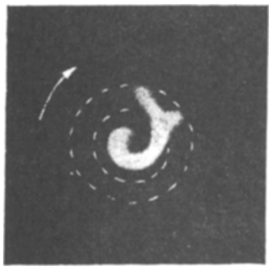


Fig. 4.

When photographs were taken perpendicular to the electrode axis (scheme of Fig. 1b) through the transparent quartz tube (observed length 480 mm) deviations of the arc from the geometric electrode axis, almost stable in position, were observed. The form of the arc is shown in Fig. 6, where the tube wall is dashed. It may be assumed that these deviations are connected with the action of the longitudinal vortex flow on the arc. In such a flow, owing to centrifugal forces the pressure along the radius of the tube is variable and has a minimum at the axis.

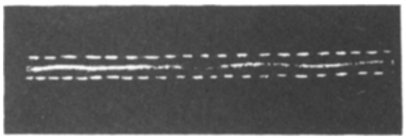


Fig. 6

The minimum pressure zone may be observed in a vortex liquid flow from the bubbles of formed in that zone as a result of cavitation. Our observations on the flow of water through a plasma generator with transparent electrodes revealed the presence of radial deviations of the minimum pressure zone from the axis similar to the radial deflections of an arc burning in a plasma generator, the bubble trajectories being spiral in form.

If we adopt the above hypothesis, it is easy to explain both the greater diameter of the projection of the axial part of the arc in Fig. 3b, and the unstable shape of the column projection, which is clearly shown in Fig. 7. This instability is accounted for by the change in arc length connected with shunting in the outer electrode [2]. The change in arc length and current oscillations are also responsible for the periodic brightness pulsations (Fig. 7), as is indicated by the fact that the shunting and brightness pulsation frequencies coincide.

5. The rate of rotation of the electrode segment of the arc in the inner electrode of the plasma generator (Fig. 1a) was measured by statistical processing of a SKS–1M record of arc rotation for 100 complete revolutions of the arc around the electrode. The results showed

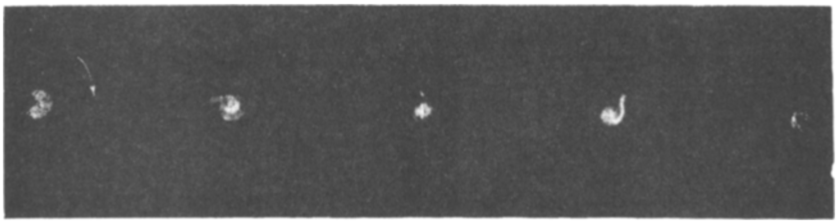


Fig. 5

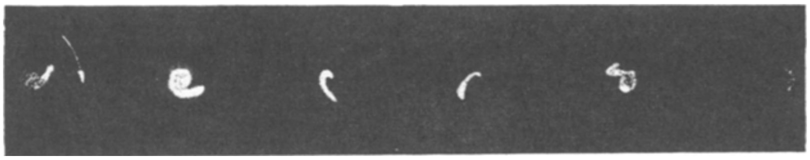


Fig. 7

that the arc rotation period was quite stable in time, and the maximum deviation did not exceed 20% of the average value, which indicates that the arc motion under the action of the gas stream is quite uniform.

Under the same conditions as those under which the arc rotation velocity was measured, we also measured the circumferential gas velocity, using a Pitot tube, at the midsection (with respect to width) of the swirl chamber at a radius corresponding to the radius of the inner electrode. It was assumed that the circumferential velocity of the gas in this section did not differ greatly from that at the inner electrode wall.

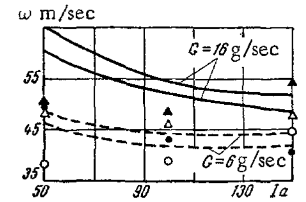


Fig. 8

A comparison of the rates of motion of the gas and the arc spot showed that the rate of motion of the electrode segment of the arc in the inner electrode of a two-chamber plasma generator is close to the velocity of the gas stream (Fig. 8). The curves given in Fig. 8 correspond to the circumferential gas velocity (the upper curve corresponds to straight polarity and the lower curve to reversed polarity for each flow rate).

Experimental values of the linear spot velocities are plotted as points. The triangular ones correspond to straight polarity (the inner electrode is the cathode) and the circular ones to reversed polarity. The solid circles are for an air mass flow rate G = 16 g/sec and the open circles for G = 6 g/sec.

It is also clear that the entrainment of the end of the arc by the flow is almost independent of polarity. Definitive conclusions concerning the dependence of entrainment on current (and other parameters) are difficult, due to the fact that the gas rotation rate and the velocity of the radial arc segment were not measured simultaneously and not strictly in the same section; while the number of available experimental points for the arc rotation rate is still insufficient to draw curves, and one can only talk in terms of a region.

Measurement of the rotation rate of the radial arc segment in the outer electrode by motion-picture photography from the flame side yielded a value for the angular rotation velocity close to that for the end of the arc in the inner electrode. The estimate is a rough one; it gave a maximum after one or even a fraction of a revolution of the spot, corresponding to elongation of the arc up to shunting.

6. From the magnitude of the luminous diameter of the arc, determined from high-speed photographs, an estimate was made of the current density in the arc spot in the current range I = 50–150 a. Corresponding graphs for two different polarities are given in Fig. 9. The continuous curve corresponds to the case when the inner electrode is the anode, while the broken curve corresponds to the when this electrode is the cathode. The average air flow rate was 14.5 g/sec for a static pressure of 5 bar in the spot zone. Clearly, there is a certain increase in current density in the spot with increase in arc current for both polarities.

A rough comparison of the luminous diameter of the spot with the diameter determined from the trace ofthe thermal effect of the arc on the electrode, observable on the electrode surface, showed that in all cases, the luminuous diameter is somewhat greater.

From data on the luminous diameter, we can estimate the specific heat flux through the arc spot. The values for cathode and anode spots proved to be quite close and of the order of $0.6 \cdot 10^9$ W/m^2 at a pressure of 5 bar and currents of 50–150 a. On the basis of what has been said so far, we can draw certain conclusions.

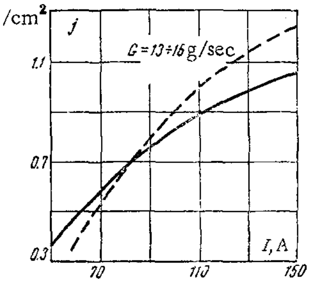


Fig. 9

The approximate correspondence of the rate of motion of the arc spot in the inner electrode and the gas velocity makes it possible to determine the latter in the current range in question from either the computed or the measured gas velocity. At small gas pressures in the plasma generator, it is necessary to take into account the possibility of arc jumping, which impairs electrode cooling in the spot. Preliminary estimates indicate that there is only a slight difference between the current densities in the anode and cathode spots in the investigated range of currents, pressures, and spot velocities.

Appreciable radial deviations of the axial part of the arc from the geometric axis of the electrodes must be taken into account in studying shunting conditions in the outer electrode of a plasma generator with vortex stabilization.

REFERENCES

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2. V. Ya. Smolyakov, "Certain properties of an electric arc burning in a dc plasma generator," PMTF, no. 6, 1963.

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