RESULTS OF AN EXPERIMENTAL INVESTIGATION OF HEAT TRANSFER IN THE DISCHARGE CHAMBER OF A PLASMA GENERATOR WITH A MAGNETIC FIELD AND A VORTICAL GAS FLOW ACTING ON THE ARC

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This paper gives the results of an experimental investigation of the heat fluxes to the electrodes of a coaxial plasmatron (plasma generator) when the directions of the gasdynamic and magnetic rotation of the arc are the same or opposite.

The most important problems which have to be overcome before powerful industrial plasma generators can be built is the maximization of the service life and efficiency of the plasmatron. These problems must be regarded as serious obstacles to extensive application of plasma heating in technological processes in the chemical, metallurgical, mechanical engineering, and other branches of industry.

In view of this, it is of great practical interest to investigate the mechanism of heat transfer in a plasmatron discharge chamber and to find methods of minimizing the heat flux to the electrodes so that the service life and efficiency of the plasmatron can be increased.

The methods commonly used at present to protect plasmatron electrodes from thermal destruction entail gasdynamic or electromagnetic displacement of the arc ends over the electrode surface so that the heat flux from the arc spot is distributed over a greater electrode surface and the time of local heating of the electrode is reduced. The literature contains very little information on the combined use of these two methods of electrode protection.

Our experiments on heat transfer in the electrode region of a plasmatron discharge chamber in which

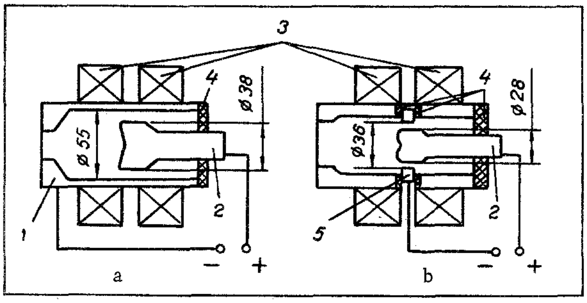

Fig. 1. Diagrams of (a) coaxial plasmatron and (b) experimental plasmatron with ring cathode: 1) cooled cathode; 2) cooled anode; 3) magnetic-field coil; 4) insulators; 5) ring cathode.

both gasdynamic and electromagnetic displacement of the arc ends was employed showed that this method is a promising one.

The experimental 500 kW coaxial plasmatron (Fig. 1a) had cooled copper electrodes and a cooled magnetic-field coil made of copper tubing. When the magnetic-field coil was connected in series in the arc circuit the magnetic-field strength in the combustion zone of the arc reached $635 \cdot 10^3$ A/m at the maximum current of 2kA. The air was injected into the chamber through either tangential or radial holes in the side wall of the chamber; in this way we could create a vortical air flow in the chamber or deliver gas to the arc region without rotation.

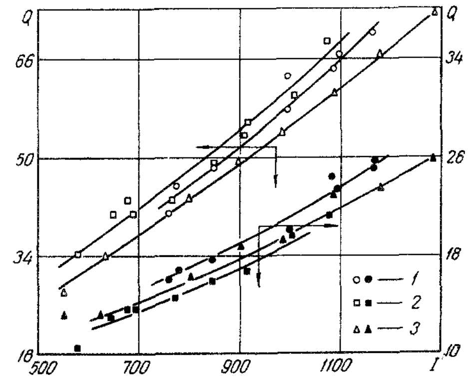

Fig. 2. Heat fluxes Q (kW) to cathode (left) and anode (right) as a function of current I (A) in the case of (1) cocurrent, (2) magnetic, and (3) countercurrent rotation of arc.

The direction of electromagnetic rotation of the arc was altered by reversing the polarity of the field coil; it was then either the same as that of the air vortex ("cocurrent rotation") or the opposite ("countercurrent rotation"). All the experiments were carried out at atmospheric pressure in the chamber.

We found by experiment that the heat fluxes to the electrodes depended on the mutual directions of magnetic and gasdynamic rotation of the arc. In the vast majority of cases, countercurrent rotation caused a reduction in the heat fluxes to the electrodes in comparison with cocurrent rotation. We also carried out experiments in which a uniform stream of nonrotating air was blown into the chamber and the arc was rotated only by the magnetic field. In this case the measured heat fluxes to the outer electrode were 10 and 5% higher on the average, and to the inner electrode 5 and 12% lower, than in the case of cocurrent and countercurrent rotation, respectively (see Fig. 2).

The presence of a vortex in the chamber alters the cross-sectional distribution of the gas flow rate and density in the chamber. The gas density and flow rate are increased at the outer electrode and reduced at the inner one, which leads to a reduction in the temperature of the gas flowing over the wall of the outer electrode and an increase in the temperature of the gas in contact with the wall of the inner electrode. This leads to a corresponding redistribution of the heat fluxes.

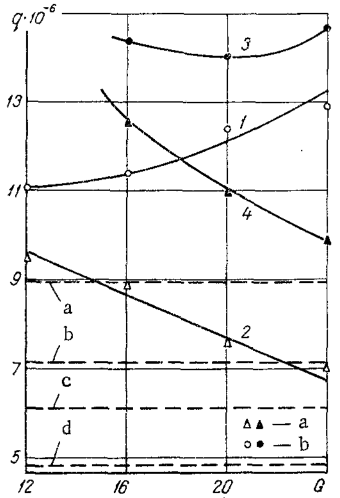

Fig. 3. Heat-flux density q (w/m^2) to ring cathode as a function of air flow rate G (g/sec) for (a) countercurrent and (b) cocurrent rotation of the arc: 1 and 2) arc current = 740 A, H ≈ 240 · 10^3 A/m; and 4) arc current = 930 A, H ≈ 295 · 10^3 A/m; A and B) heat fluxes from cathode spot at currents of 930 and 740 A, respectively, calculated from published data; C and D) the same according to experimental data of authors.

The reduction in the heat fluxes to the electrodes with countercurrent rotation as compared with cocurrent rotation is of greatest interest. The gas density and flow rate distributions over the cross section of the chamber can be regarded as virtually identical in both cases. This raises the question of whether this reduction in heat fluxes is due to a reduced delivery of energy to the electrode walls from the arc spots, or whether it is of some other nature.

In the usual coaxial plasmatron shown in Fig. 1a, the difference between the heat fluxes to the electrodes with countercurrent and cocurrent rotation reached 14%. It should be borne in mind that the measured heat fluxes to the electrodes in this plasmatron are the sum of the heat fluxes from the arc spots, the convective and radiative heat fluxes from the arc column, and the convective and radiative heat fluxes from the plasma stream flowing over the electrode wall. Under these conditions it is difficult to determine whether this change in the total heat fluxes is due to a change in the heat fluxes in the arc-combustion zone, or if it is merely due to change in the total heat removal to the electrodes outside the arc-combustion zone. The total heat flux to the electrode depends, of course, on the position of the combustion zone along the electrode, since this determines the area of electrode surface over which the plasma stream flows. Hence, we made measurements of the position of the arc-combustion zone on the cathode with countercurrent and cocurrent rotation from the tracks left by the arc on the cathode. We found that in the case of cocurrent rotation the arc burned closer to the exit part of the cathode than with countercurrent rotation and, hence, the difference in heat fluxes cannot be attributed entirely to the change in heat flux due to a change in the arc-combustion zone. It is difficult, however, to conclude from the obtained data whether this change in heat fluxes is due to a change in the flux at the arc spots, since the indicated difference in heat fluxes was obtained under conditions in which the voltage with countercurrent rotation was lower than with cocurrent rotation. The indicated difference in temperatures might be due to the difference in heat fluxes from the plasma stream itself. This is indicated by the fact that although the heat flux to the electrodes with countercurrent rotation was less than with cocurrent rotation, the relative loss (referred to the power of the stream) for countercurrent rotation was greater in several regimes than for cocurrent rotation.

For a more accurate assessment of the effect of countercurrent gasdynamic and magnetic rotation of the arc on the heat fluxes to the electrodes, we had to get rid of the heat brought to the electrode by the plasma stream itself. To do this we altered the design of the cathode, which was constructed in the form of a cooled copper ring, 10 mm wide and with an inside diameter of 36 mm, electrically insulated from the other parts of the chamber (Fig. 1b). The electric insulation also acted as heat insulation and prevented leakage of heat from the cathode. The other components of the apparatus, including the anode and

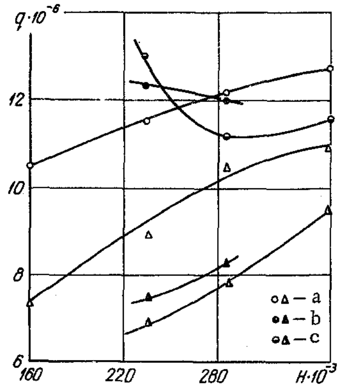

Fig. 4. Heat-flux density q (W/m^2) to cathode at an arc current of 740 A as a function of magnetic-field strength H (A/m) for cocurrent (circles) and countercurrent (triangles) rotation: a) G = 16; b) 20; c) 24 g/sec.

the field coil, were the same as before. The experiments were carried out with an anode 28 mm in diameter. The duration of each separate experiment was limited by the thermal strength of the cathode insulation and was a maximum of 60 sec, after which the insulation had to be replaced.

The experiments on the modified apparatus showed that the difference in heat fluxes to the cathode with countercurrent and cocurrent rotation reached 45% in some regimes. All other conditions being equal, this difference increased appreciably with increase in the gas flow rate (Fig. 3) and decreased with increase in the magnetic-field strength. An increase in the magnetic-field strength also caused a general increase in the level of heat fluxes to the cathode (Fig. 4).

It is of interest to compare the measured heat fluxes to the cathode with the heat fluxes at the cathode spots, and these can be calculated from available published data [1–3]. We assume that the heat flux in the cathode spot is given by the expression

$$Q = I(\Delta U_c - \varphi). \tag{1}$$

According to several authors, for copper $\Delta U_c = 15–16$ V and the electron work function for an oxidized copper cathode is 5.2 V. The specific heat fluxes to the cathode calculated from these data are shown by a dashed line in Fig. 3 (ΔU_c was taken as 16 V). An examination of Fig. 3 shows that the total heat fluxes were never less than the heat fluxes calculated from the cathode spot. Hence, the change in heat flux in the arc zone with countercurrent and cocurrent rotation can be attributed either to a change in the convective and radiative components of the heat flux in the arc zone or to a change in the heat flux from the cathode spot.

It should be borne in mind, however, that there are no reliable published data on voltage drops near the electrodes for blown arcs moving at high speed in magnetic fields. The available published data relate to freely burning arcs. Hence, we carried out special experiments to determine the value of $(\Delta U_c - \varphi)$ in expression (1).

For this purpose we measured the heat fluxes to cathodes in the form of water-cooled copper rings of different widths (11.5 and 4.5 mm). The amount of heat arriving at the cathode from the arc spot does not depend on the width of the cathode ring, whereas the total convective and radiative heat flux from the arc column is directly proportional to the heated (inside) surface of the ring. From the difference in heat fluxes in rings of width 11.5 and 4.5 mm we measure the density of the total convective and radiative flux from the arc column

$$q_{cr} = \frac{Q_{m1} - Q_{m2}}{S_1 - S_2}.$$

From these data we can determine the total convective and radiative heat flux to the ring cathode

$$Q_{cr} = q_{cr} S.$$

Then the heat flux entering the ring cathode from the cathode arc spot is

$$Q_{ent} = Q_m - Q_{cr}.$$

Knowing the value of Q_s, we can determine the value of $(\Delta U_c - \varphi)$ by using expression (1). The experimentally determined value of $(\Delta U_c - \varphi)$ was 7.4 V. This value determined at a current strength $I = 600$ A and a magnetic field $H \approx 190 \cdot 10^3$ A/m at atmospheric pressure with air as the working fluid.

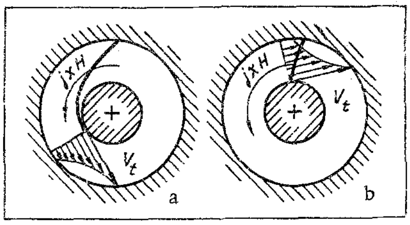

Fig. 5. Scheme of interaction of arc with magnetic field and vortical gas flow in the case of (a) cocurrent and (b) countercurrent rotation.

Thus, experiments show that the total convective and radiative heat flux in the arc zone may exceed the heat flux from the arc spots (Fig. 3).

It should be noted, however, that the cited value of $(\Delta U_c - \varphi)$ at 7.4 V does not take into account the energy spent on melting and evaporating the cathode material, since we did not measure the rate of removal of cathode material in the experiment. We can merely state that, according to visual estimates, the destruction of the cathode during the entire period of the experiments was very slight.

In addition, experiments with rings of different widths showed that the value of $(\Delta U_c - \varphi)$ was the same with cocurrent and countercurrent rotation. This confirms the hypothesis that the change in the heat flux to the electrodes with countercurrent and cocurrent rotation is due entirely to the convective and radiative components of the flux from the arc column.

It should be noted that with cocurrent rotation the total heat flux in the arc-combustion zone increases with increase in the gas flow rate, whereas with countercurrent rotation a similar increase in gas flow rate leads to a reduction of the heat flux. This can be explained in the following way. In a coaxial plasmatron the arc column has a helical form owing to the action of electromagnetic forces. The forward end of the helix in the direction of helix is motion at the inner electrode (see Fig. 5).

In the annular gap between the electrodes the gas velocity distribution is subject to the law of conservation of momentum, if friction is neglected, i.e.,

$$V_t R = \text{const}.$$

This means that the tangential gas velocity at the inner electrode (anode) is greater than that at the outer electrode. Hence, in the case of cocurrent rotation the gasdynamic forces tend increasingly to "draw out" the arc helix, whereas in the case of countercurrent rotation the arc is "compressed" and becomes nearly radial in form.

An increase in gas flow rate in the first case leads to elongation of the arc helix and, hence, to an increase in the convective and radiative heat flux from the arc column, while in the second case it leads to a reduction in the length of the arc and its approximation of radial form, which leads to a corresponding reduction in the radiative and convective heat flux in the arc-combustion zone. An increase in the magnetic field reduces the effect of gasdynamic forces in comparison with that of electromagnetic forces and there is a corresponding reduction in the difference between the heat fluxes in the case of countercurrent and cocurrent rotation.

Thus, a change in the mutual direction of the electromagnetic and gasdynamic forces acting on the electric arc in a plasmatron can have a significant effect on the heat fluxes in the hottest region of the electrode in the arc-combustion zone. Depending on the relative direction and magnitude of the electromagnetic and gasdynamic forces, the heat flux in the arc-combustion zone on the cathode at constant current strength may vary by a factor of 2, which indicates a significant effect on the electrode operating conditions. The obtained result, besides other things, indicates a high level of convective and radiative heat fluxes in the arc-combustion zone, which in toto may even exceed the heat flux from the moving arc spot. This must be taken into account in calculation of the cooling of the electrodes.

NOTATION

I is the current; ΔU_c is the cathode voltage drop; φ is the electron work function of the cathode material; q_{cr} is the density of combined convective and radiative heat flux to the cathode; Q_m is the measured heat flux to the cathode; S is the area of the inside surface of the ring cathode; Q_{cr} is the combined convective and radiant heat flux to the cathode; Q_s is the heat flux entering the cathode from the arc spot; V_t is the tangential gas velocity; R is the radius; j is the current density; H is the magnetic field strength.

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