EXPERIMENTAL INVESTIGATION OF CATHODE SPOTS ON METALLIC ELECTRODES PROTRUDING IN PLASMA FLOW

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The behavior of cathode spots on metallic electrodes is investigated. The dependence of the basic characteristics of the spots (current per spot, life time, rate of displacement, average area and so forth) on the nature of the flow of the plasma past the surface of the electrode, the surface temperature of the electrode, the total current in the electrode, and the magnetic field is obtained. The investigations were done in connection with the study of the operation of electrodes of open cycle magnetohydrodynamic generators. The experiments were conducted with copper electrodes introduced in the plasma formed by the combustion products of natural gas with potassium added to it.

The investigation of the operation of cooled metallic electrodes of MHD generators showed that at currents of the order of a few tens of amperes per cm the cold boundary layer formed at the surface of the electrodes breaks down and a constricted discharge occurs. The arcs forming in the boundary layer rest on the cathode spots on the electrode surface.

The behavior of the spots and their characteristics determine the most important parameters of the electrode: the electrical characteristics [1] and the erosion of the material from the cathode.* In order to estimate the local erosion of the electrodes and the near-electrode voltage drop, it is necessary to know the basic characteristics of the cathode spots [2], in particular, the area of a single spot, the magnitude of the current flowing through the spot, the life time, and the rate of displacement.

Isolated quantitative investigations of cathode spots on plane metallic electrodes were done in [3, 4]. In view of the inadequate spatial and temporal resolution of the equipment used in these investigations relatively large and stationary spots were studied. The investigations were done either at separate values of the current at the electrode or in a range of relatively small currents.

The object of the present work is to determine the basic parameters of cathode spots on electrodes in the channel of a MHD generator for different temperatures at their surfaces and different current intensities, and also to investigate the effect of the magnetic field on the behavior of the spots. It is a continuation of [5]. The investigations were extended in respect of the current range by a factor of few and by an order of magnitude in respect of the spatial and temporal resolution of the equipment.

Hemispherical electrodes made of oxygen-free copper protruding into the plasma flow were used for the investigations; as the earlier investigations had shown [5], they had minimal erosion and the best electrical characteristics.

The experiments were conducted in the channel of the MHD generator of the large experimental installation U-02 [6]. The length of the channel is 600 mm, the height in the direction of the magnetic field is 90 mm, and the width 180 mm. The plasma flux consisted of the combustion products of methane in pre-

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*V. V. Kantsel', "Experimental investigation of the region near the cathode of an electric arc discharge with high time resolution," Candidate's Dissertation, Moscow (1973).

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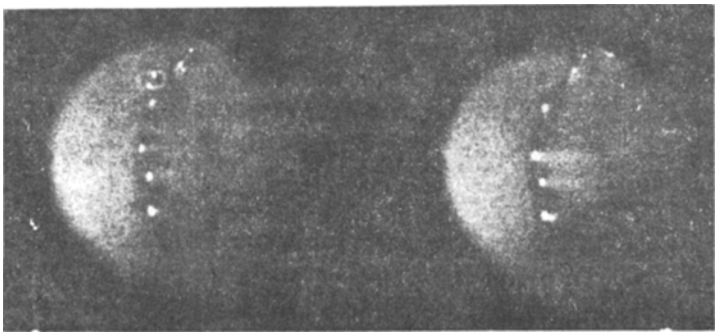

Fig. 1

heated air enriched with oxygen with addition of potassium salts as the ionized additive. The velocity of the core of the plasma flux was 300-500 m/sec at a pressure of 0.7-0.9 atm in the channel. As a rule the plasma temperature in the core was 2550-2700°K for air enriched with oxygen up to 45% and heated to 1300°K. The amount of additive fed in the form of 50% aqueous solution of potassium varied from 0.4 to 0.7 in molar content of potassium.

The flow rates of the gas, air, oxygen, and the additive, the heating temperature of the air, and the static pressure in the operating part of the channel were measured during the experiments; the plasma temperature at the entrance into the channel was determined by the method of reversal of D-lines of sodium. The electrode temperature was measured with a chromel–alumel thermocouple embedded into the electrodes at a depth of 2-3 mm from the surface. The heat fluxes to the electrodes were measured from the flow rate and the heating of the cooling water.

The electrode was made of oxygen-free copper; it had a hemispherical shape with 40-mm diameter and protruded 40 mm into the flow.

Two types of electrodes with different distances from the surface swept by the flow to the water cooling (12 mm, electrode M12 and 50 mm, electrode M50) were used in the experiments. The average surface temperature in the absence of current at the electrodes was 400-450 and 600-650°K for M12 and M50 respectively, as determined from the heat fluxes. During the passage of current through the electrodes the average temperature of the electrode surface increased due to additional heat fluxes of 15-30 W/A from the cathode spots into the electrodes; at 100 A the temperature was 480-530°K for M12 and 850-950°K for M50.

High-speed photography was used for studying the behavior of the cathode spots; this was done with an SFR-L high-speed photographic recorder operating in the time "loop" mode. The rate of photographing was 40,000 to 120,000 frames per second. In view of the fact that for the establishment of steady temperature of the electrode surface the photographs were taken during prolonged operation of the electrodes, while SFR-L is intended for photographing transient processes, the standard shutter of SFR-L was replaced by a central shutter with small response time in order to avoid superposition of frames on the photographic recorder. For ensuring the necessary spatial resolution an additional optical system was used which made it possible to take photographs with different relative magnification.

For determining the instantaneous values of the current flowing through the spot, oscillographs of the current were taken synchronously with the photographs. The magnitude of the current flowing through the electrode was measured in the range 15-100 A; the magnetic field varied from 0 to 1.7 teslas. In order to obtain large currents the induced electric field was directed along the applied field, i.e., the channel of the MHD generator operated in the "braking" mode. The behavior of the cathode spots changes little in passing from the induction to "braking" mode. This was noted in [7], where it was shown that only the sign of the electric field in the core of the flow changed.

The area of the cathode spots and the rate of their displacement were measured with a S15A/G microscope. For this purpose a special attachment was mounted on the movable carriage of the microscope moving along x and y axes; with this attachment the points on the photographic records could be determined quite accurately in relation to the fixed axes and the coordinates of the spots could be determined. The spot was then photographed on a photographic film, after which it was projected on a magnified scale. As a result the linear dimensions of the cathode spots were increased 50 times. The error in the measurement of the dimensions was ~20%.

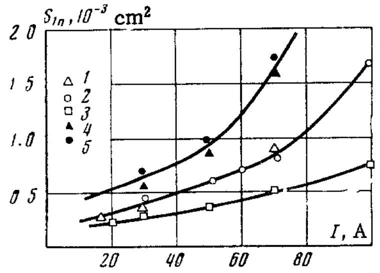

Fig. 2

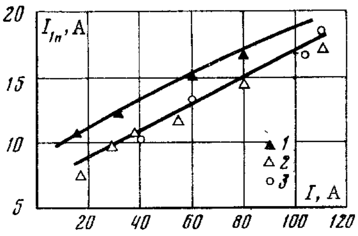

Fig. 3

The rate of displacement of the cathode spots was measured by successive superposition of the magnified projections of the spots on a tracing paper, on which the contours of the spots in relation to the fixed coordinate axes were successively traced. Thus the pattern of movement of the spots could be determined and the rate of displacement could be measured with an error of ~15%.

The development and burning of cathode spots on hemispherical copper electrodes in the channels of open-cycle MHD generators are described in [5, 6]. In the absence of current between the electrodes the entire surface of the electrode is coated with a layer of the additive having a thickness of ~ 0.3-1 mm. For an average current density of 50-200 mA/cm^2 cathode spots develop on the cathode in the form of sparks, which rapidly move to the center of the cathode under the action of the flow, cleaning the electrode surface of the additive layer in its path. A sharp discontinuity in the volt–ampere characteristic occurs with the appearance of the first cathode spots: a large increase of the current occurs for a small voltage increase. As the current through the electrode increases, the cathode spots become more intense and increase in number; as a result the first half of the electrode swept by the oncoming flow is rapidly cleaned of the visually noticeable additive layer which remains on the second half of the electrode, where burning arcs are not observed.

Starting from currents of 15-20 A the cathode spots are largely concentrated in the central part of the electrode (Fig. 1). The locations of the spots in this zone coincide quite accurately with the boundary of separation of the flow and the boundary layer in the turbulent flow past a hemisphere. Since cathode spots do not appear in the second half of the electrode, i.e., in the vortex zone (in the investigated range of currents), the boundary of the additive layer with the clean surface of the electrode is formed in the zone of separation of the flow where the spots are concentrated. For other configurations of the electrode, for example, wing-shaped, the main seat of the cathode spots is also the zone of separation of the flow [6]. A similar pattern of burning of the spots in the zone of separation of the flow is observed also on cylindrical electrodes [8]. With the increase of the electrode surface temperature from 400 to 600-700°K the qualitative pattern of the development and burning of the cathode spots remains essentially unchanged.

The following basic characteristics of the behavior of the cathode spots can be noted from the obtained experimental data.

The behavior of the cathode spots depends significantly on the zone in which they burn. Starting from currents of 15-20 A the frequency of appearance of the spots in the zone of separation of the flow many times exceeds the corresponding frequency in the zone of unseparated flow past the electrode. In the zone of the oncoming flow the spots generally move gradually in the direction of the flow with a velocity $\sim 2 \cdot 10^2$ cm/sec; they have relatively small areas and their life time is small (100-200 μsec). In the zone of separation of the flow the velocity of the spots is on the average smaller by an order of magnitude and they move randomly (as the additive gets evaporated) within regions comparable with their dimensions. The area occupied by a single spot is 1.5-2 times larger than in the zone of impact of the flow (Fig. 2, curves 1, 2 – areas of a single spot in the zone of separation of the flow; 3 – areas of a single spot in the zone of impact of the flow).

With the increase of the current in the electrode from 15 to 100 A the frequency of appearance of the spots increases from 2-5 to 10-15 kHz; the average life time of the spots in the zone of separation of the flow increases simultaneously (from 150-200 to 600-800 μsec) and the most probable number of simultaneously burning spots also increases (from 1-2 to 7-9). A joint analysis of the oscillograms and the photographic records shows that with the electrode current from 15 to 100 A the average magnitude of the current per spot increases (Fig. 3, curve 1 – dependence of the average current passing through one spot

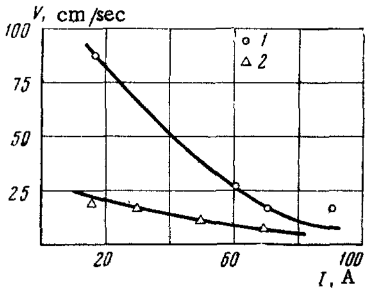

Fig. 4

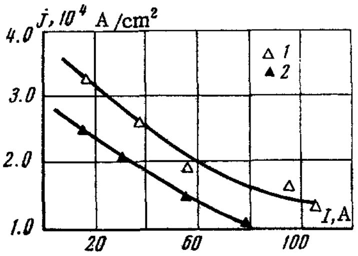

Fig. 5

on the total current for the electrode with surface temperature 600-700°K; 2 – dependence of the average current passing through one spot on the total current for the electrode with surface temperature 400–450°K in the absence of magnetic field; 3 – the dependence of the average current passing through one spot on the total current for the electrode with surface temperature 400–450°K in a magnetic field of 1.7 tesla).

On increasing the average current from 15 to 100 A, the velocity of the cathode spots decrease many times in the presence of magnetic field B = 1.7 tesla as well as in the absence of the magnetic field (Fig. 4, curve 1 – the dependence of the velocity of the cathode spots on the total current through the electrode with surface temperature 400–450°K for B = 1.7 tesla; 2 – for B = 0).

The average current density in the spots decreases from 2.5-3.5 · 10^4 to 1-1.5 · 10^4 A/cm^2 (Fig. 5, curve 1 – the dependence of the current density in the spot on the total current passing through the electrode with surface temperature 400-450°K; 2 – with surface temperature 600-700°K) and the area of the spots increases sharply (see Fig. 2, curves 1, 2 – areas of cathode spots on the electrode with surface temperature 400–450°K; 4, 5 – with surface temperature 600-700°K).

In the presence of a magnetic field (B = 1.7 tesla) the spots on the electrode with surface temperature of 400-450°K acquire large velocities in the zone of separation (see Fig. 4, curve 1). They move more in a directed manner and are concentrated at the upper and lower edges of the electrode.

The lifetime of the spot decreases with the application of the magnetic field, while the frequency of their appearance increases 1.5-2 times. With the increase of the surface temperature of the electrode to 600-700°K the application of the magnetic field does not affect the above characteristics. In the entire range of investigated temperatures of the electrode the magnetic field has no effect on the area of the spots (see Fig. 2, curve 2 – area of cathode spots on the electrode with surface temperature 400-450°K for B = 1.7 tesla; 5 – area of cathode spots on the electrode with surface temperature 600-700°K for B = 1.7 tesla), the current per spot (see Fig. 3), and the most probable number of the spots.

For identical average current in the electrode the increase of the surface temperature from 400-450 to 600-700°K results in an increase in the area of the spots by a factor of 1.5-2 (Fig. 2, curves 1, 4), a very small decrease in the most probable number of the spots, and an increase of the average current per spot.

These characteristics in the behavior of the cathode spots are related to the characteristics of operation of cold electrodes in the channel of an MHD generator, which are observed in the flow of a low-temperature plasma past the electrode surface and in the formation of relatively cold gasdynamic and thermal boundary layers having large electrical resistance.

Because of the low surface temperature of 400-700°K the electron emission from the electrode is small; therefore for large voltages between the plasma and the electrode a thin zone of space charge with large gradient of the electric field is formed at the surface of the electrode; the passage of current through this zone is ensured by the diffusion of ions to the surface [9]. When an electric field sufficient for the breakdown develops at the surface of the electrode, cathode spots appear at the surface of the electrode.

The breakdown voltage decreases with the decrease in the thickness of the boundary layer, since the thickness of the space charge zone decreases, which results in an increase of the electric field at the surface of the electrode.

Three zones are formed on the surface of electrodes protruding in a plasma flow: 1 – zone of impact of the flow, in which the boundary layer is small and the velocity gradient near the surface is quite large; 2 – zone of separation of the boundary layer, in which the velocity gradient of the flow near the surface is nearly zero; 3 – the vortex zone. Since the thickness of the boundary layer is minimum near the pole of the hemisphere, the first microarcs develop just in this zone. Perhaps under the action of the oncoming flow, whose velocity gradient in this zone is quite large (i.e., the velocity of the flow past the arc near the surface is also relatively large), the region of compression of the arc column near the spot shifts in the direction of the flow. As a result the concentration of electrons and ions increases over the part of the surface of the cathode spot located down the flow. According to [10] this asymmetry in the distribution of ion and electron concentration and current density in the spot may lead to the result that this part of the spot gets heated more intensively, due to ion bombardment and the cathode spot moves to a new location (down the flow in the present case).

As the near-electrode voltage drop increases with the increase of the average current flowing through the electrode conditions for electrical breakdown and formation of spots appear also in the zone of separation of the flow; this is observed starting from I = 15-20 A. Electrical arcs, which burn in the zone of separation of the flow, are practically unaffected by the oncoming flow, since in this zone the velocity gradient of the flow at the surface is nearly zero. Therefore the cathode spots in this zone move randomly with a velocity of $1\text{-}2 \cdot 10$ cm/sec, i.e., an order of magnitude smaller than in the zone of impact of the flow.

The conditions for burning of the cathode spots in the zone of separation of the flow are more favorable than in the zone of impact because of its smaller effect on the arcs and the formation of the boundary between the additive and the "clean" surface. Therefore the cathode spots burn preferentially in the zone of separation of the flow and here the frequency of their appearance is large.

With the increase of the average current through the electrode the near-electrode drop in the plasma-electrode voltage increases; as a result the probability of formation of new spots increases. This leads to the result that with the increase of the average current the frequency of appearance of the cathode spots increases and, hence, considering the increase in the life time of the spots the number of simultaneously burning spots also increases.

The mechanism of formation of the spots on the electrodes in the channel of an MHD generator perhaps differs significantly from the mechanism operating during the operation of electrodes in ordinary gases or in vacuum, where the number of cathode spots increases with the increase of the average current mainly because of the breaking up of the cathode spot (see footnote on p. 159) as a result of which the average current per spot and the average area of a spot remain constant on increasing the total current. On the electrodes in the channel of an MHD generator the increase in the number of cathode spots with the increase of the total current occurs mainly due to new breakdowns and the area of a spot and the average current per spot increase.

The change in the velocity and dimensions of the spots is probably also caused by the fact that with the increase of the average current flowing through the electrodes in the MHD generator for a long time the surface temperature increases. With the increase of the surface temperature the cathode material (copper) interacts with chemically aggressive medium in the channel considerably more actively; as a result oxide films are formed on the electrode. Cathode spots burning on oxide films have larger dimensions and their velocity and the current density in them decrease.* The significant increase of the area of the cathode spots with the increase of the surface temperature of the electrodes from 400 to 600-700°K can be also explained by more intensive formation of oxide films. A secondary reason for the increase of the area of the spots with the increase of the electrode temperature may be the marked decrease of the thermal conductivity of copper near the surface of the electrodes and especially around the spots.

The magnetic field has a significant effect on the behavior of cathode spots. At high pressures in different gases cathode spots acquire velocity directed in accordance with Ampere's rule under the action of the magnetic field.

On cold copper electrodes in the zone of impact of the flow the magnetic field has practically no effect on the motion of the cathode spots, since in this zone the velocity gradient of the flow near the surface is large and the flow directs the arc against the force acting on it from the side of the magnetic field. Since the action of the flow predominates, the spot does not change its direction in the presence of the magnetic field. In the zone of separation of the flow the cathode spots acquire more directed motion. Since for B = 1.7 tesla the Hall effect develops ($\omega\tau = 1\text{-}1.5$), the cathode spots are concentrated mainly in the upper and lower parts of the electrode.

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