CATHODE SPOTS ON ELECTRODE SLAG FILMS IN AN OPEN-CYCLE MHD GENERATOR

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UDC 621.313.12:538.4

A study has been made of the function of the electrodes (cathodes) in an open-cycle MHD generator for several different reasons [1-3], because the electrode processes have marked effects on the erosion and electrical characteristics of the electrodes. The specific features of the conditions in an MHD generator channel include, particularly, the high-temperature plasma composed of combustion products together with the deposition of potassium salts on the electrodes. These factors have a marked effect on the behavior of the cathode spots. In the case of an MHD generator fueled by coal, the plasma contains the incombustible mineral part of the fuel (ash). Therefore, the electrode surfaces receive not only potash salts, but also slag, which consists of various refractory oxides that differ from the potassium compounds in electrical conductivity, thermal conductivity, and emissivity. These films may substantially affect the parameters of the cathode spots, and hence the erosion, and the values may differ substantially from those given in [3]. We have examined the major features of the cathode spot behavior for an open-cycle MHD generator fueled by coal.

The tests were performed with the large experimental U-02 open-cycle MHD generator [4]. The channel length was 600 mm, width 180 mm, and height along the magnetic field 90 mm. The plasma consisted of combustion products from natural gas burned in an air mixture enriched to 50% in oxygen and previously heated to 250°C with the addition of potassium salts as ionizing additives. The mineral component of the fuel was supplied as the ash from Kuznetsk coals grade T in an amount equivalent to the combustion of the corresponding amount of coal, this constituting 1% of the total flow rate of combustion products. The slag deposited on the electrodes was analyzed at the Dzerzhinskii All-Union Heat-Engineering Institute, and the following values (%) were found: SiO_2 45.1; Al_2O_3 19.4; Fe_2O_3 12.8; CaO 3.5; K_2O 13; TiO_2 1.4; MgO 1.3; Na_2O 0.2, together with certain other oxides. The temperature at the core of the flow was 2470-2520°K, with a flow speed of 350 m/sec and a pressure in the channel of 0.75-0.9 atm (1 atm = 98.0665 kPa).

The behavior of the cathode spots was examined by high-speed photography, with an SFR-L camera working at rates from 40,000 to 120,000 frames/sec. At the same time, an oscilloscope recorded the electrode current.

The area and speed of the cathode spots were measured by the method described in [3].

The measurements were made on electrodes composed of oxygen-free copper (surface temperature 400°C) and a chromium alloy (surface temperature 1100°C), the shape being hemispherical of diameter 40 mm and projecting into the plasma to a distance of 40 mm. Also, we examined silicon carbide electrodes (surface temperature 1350-1400°C) and also ones of zirconium dioxide containing 20% zirconium diboride (surface temperature 1350-1400°C), which took the form of cylinders of diameter 40 mm projecting 10 mm into the flow.

A slag film was deposited comparatively rapidly (within a few minutes) in the absence of a current, and this had a low thermal conductivity (about 1-1.7 kcal/m·h·deg), the thickness being 2-3 mm, as measured after removing the electrodes. The temperature of the surface layer of the film was measured with an optical pyrometer and was found to rise rapidly to the melting point (1450-1500°C), and, consequently, the surface showed the characteristic waves of a liquid film flow (Fig. 1). Cathode spots appeared if currents more than 2-4 A were passed by the cathode.

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 4, pp. 29-33, July-August, 1976. Original article submitted September 8, 1975.

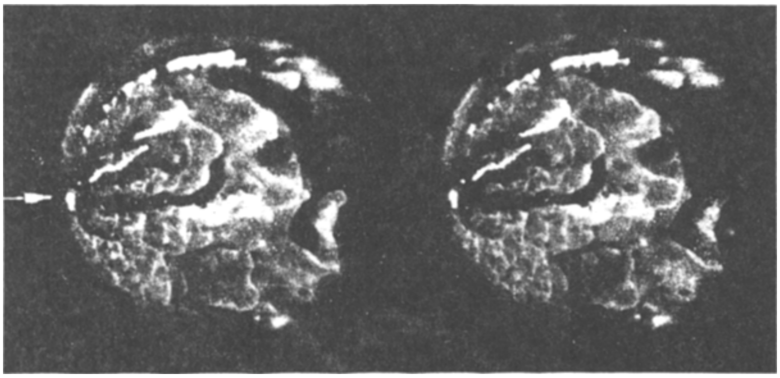

Fig. 1

The flow over the surface is governed by the shape of the electrode, so the pattern taken by the cathode spots varies with the shape [3, 4]. Consequently, the two groups of electrodes – hemispherical and cylindrical – behave in different ways.

A hemispherical electrode showed spots only on the first half of the surface, even in the absence of slag (Fig. 1); at currents below 20 A, there were mainly single spots, whose points were disposed at random on the first half of the electrode. As the current was raised to 50 A, the number of spots increased, and chains of cathode spots arose in the zone covered by the wandering, whose direction coincided with the flow direction.

The cathode spots tended to evaporate the slag, and this produced regions free from visible slag films. These regions enlarged as the current was increased, but no sharp boundary between two parts of the electrodes was formed in the fashion found when potassium salts are deposited (KOH and K_2CO_3), for in the latter case the spots remove all visible signs of a layer of these compounds within a few minutes, and a sharp boundary appears in the central part of the electrode. The rear of the electrode then has a thick film. This would appear to be because the deposition rate for the slag film (least for electrodes projecting into the flow) is larger by an order of magnitude than that for films of potash salts alone. If we assume that the attachment coefficient is close to 1 for slag particles colliding with the surface when a reasonably sticky film is present [5], then the deposition rate in our experiments would be $1.5 \cdot 10^{-2}$ g/cm$^2 \cdot$ sec. Further, the rate of erosion of the slag film by the cathode spot was found to be much less than that for potassium compounds.

Therefore, slag films on the incident side provide favorable conditions for cathode spots, since there is always a boundary between the clean surface and the slag film, and the spots tend to settle there. Further, the spots burn on the slag film. Around these spots on the films there are fairly extensive regions in which the temperature exceeds the mean temperature of the film considerably. Such regions arise probably from the low thermal conductivity (especially near the contact with the metal) and the electrical heating of the film by the current flowing through it.

We measured the major parameters of the spots (mean speed, mean area, most probable number, current density, and so on) and found that spots on the incident side were smaller, moved faster, and had higher current densities, as in the case where there was no slag [3].

However, the slag films caused the most likely number of spots on a copper electrode to alter considerably by comparison with the data of [3], and the same applies for the current density in the spots and so on. Figures 2 and 3 show the most probable number of spots N_{mp} (Fig. 2) and the mean current density in a spot (Fig. 3) in relation to the total current through the electrode (curves 1 represent the parameters for an electrode made of oxygen-free copper; 2 are the same for the chromium alloy; 3 are those for zirconium dioxide containing zirconium diboride; and 4 are for silicon carbide). It is clear that the spot area and number of spots on a copper electrode are larger than those given in [3] by almost an order of magnitude, while the current density is correspondingly reduced by two orders of magnitude to $3\text{-}1.3 \cdot 10^2$ A/cm^2. A similarity to the case of clean conditions was that the number of spots increased with the electrode current, while the current densities in the spots decreased appreciably. The speeds were almost unaltered at $1\text{-}2 \cdot 10^2$ cm/sec on the incident side or $2\text{-}4 \cdot 10^1$ cm/sec on the lee side. The mean spot lifetime was increased to 1.5 msec.

The spots appeared over virtually the entire surface in the cylindrical case, but here again they burned only at the boundary between the film and the clean surface, and sometimes there were clumps of spots around an isolated patch of film. In general, the trends were the same as for the hemispherical electrode.

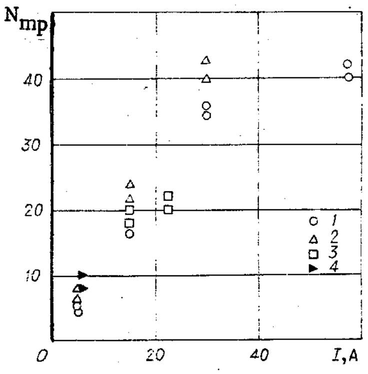

Fig. 2

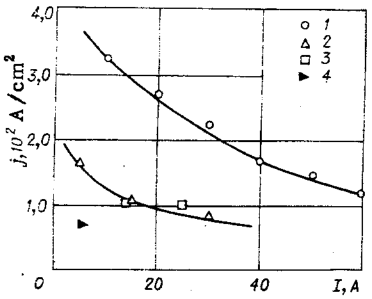

Fig. 3

A fall in the thermal conductivity of the cathode material [6] increases the area and lifetime of the cathode spots; the same effect is produced by raising the mean surface temperature of the electrode [3], so a rise in surface temperature simultaneous with reduction in the thermal conductivity should increase the lifetime and area very considerably. In our case, the thermal conductivities of the materials varied widely, being 3.8 for oxygen-free copper, 0.7-0.8 for the chromium alloy and silicon carbide, and 0.03 W/cm·deg for zirconium dioxide containing 20% zirconium diboride. The surface temperatures of the electrodes varied from 400 to 1300-1400°C. These marked differences in thermal conductivity and temperature for the materials had comparatively little effect on the spot parameters: the areas increased by a factor 2.5-3, while the most probable number of spots altered only slightly.

The thermophysical parameters and electrode temperature have this rather small effect because the slag film takes up roughly a constant temperature (1500-1600°C at the surface) and a roughly constant thickness when a current is present, the thickness being such that the film bearing the spot acts as a massive cathode. In fact, the film thickness estimated from the surface temperature, heat flux, and thermal conductivity of the slag in the presence of the current was not less than 0.5-1 mm. Consequently, the electrode material acts as a substrate, and therefore the thermophysical parameters and temperature of the latter have no marked effect on the spot parameters. The basic concepts [7] on the effects of spot parameters on the electrical characteristics of electrodes indicate that the overall effective potential difference near the electrode with respect to the plasma should differ little from one material to another. Also, the comparatively large sizes and numbers of the spots probably reduce the potential difference near the electrode substantially [7] by comparison with the value in the absence of slag. Measurements on the U-02 showed that the potential differences near the electrodes were fairly small in the presence of slag films and varied little from one electrode to another [8].

Therefore, slag films play an active part in reducing the potential differences near the electrode and also should reduce the local erosion resulting from the spots. However, the slag may increase the chemical erosion considerably, so the electrode material must be chosen with particular emphasis on resistance to slag.

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CUMULATIVE EFFECT OF A SHOCK REFLECTED FROM A SPHERICAL CONCAVE WALL

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UDC 533.6.011.72

The cumulative effect originating during shock reflection from a cylindrical concave wall at the end of a rectangular shock-tube channel is described in [1]. The intensity of the reflected wave (the Mach number M) hence grew ~ 1.5-fold as compared with the case of wave reflection from a flat wall.

Experiments were performed in a shock tube whose construction is similar to that described in [2]. The shock-tube chamber and channel were fabricated from ordinary steel tubing with a 208 mm inner diameter. The measuring section, a steel tube with 120 mm inner diameter, was placed at the end of the channel. The forward part of this tube with sharp edges was set deep in the channel with such a design that the wave running between the channel walls and the measuring section would not influence the flow in the latter during the experiment. Acetate cellulose films 0.2 mm thick in two layers were used as the working diaphragm. Air was on both sides of the diaphragm; at atmospheric pressure in the channel and at a 2.5 gage atm pressure in the chamber; the shock-wave Mach number was 1.27 ± 0.01.

Presented in Fig. 1 is a diagram of the measuring section apparatus, where the experiment was performed. The ends of the measuring section were compactly plugged by the organic glass entrance plug 1. The plug end face had a hollow in the form of a spherical cup. A ~ 1-mm-wide slit 2 was sawed through the body of the plug. The plane of the slit coincided with the axis of the measuring-section tube. Two ~ 10-mm-wide windows 3 in which glass with flat surfaces was set were cut out of the measuring section wall. A 0.4-0.5-mm-wide regulatable slit was mounted on the outer surface of one of the windows. During assembly of the measuring section and its apparatus in the shock tube, the shock-tube axis, the slit in the plug, the windows in the walls of the measuring unit, the regulatable slit, and the optical axis of the photorecording system were all in one plane.

The process of shock reflection was recorded by using an IAB-451 shadowgraph and a coupled SFR camera in the photo-chronograph mode. An IFK-120 pulsed light source was used for bias lighting. Start-up of the light source was accomplished by a pulse from a piezosensor.

The shock-tube diaphragm was broken by using the electrical explosion of a wire. This permitted synchronization of shock tube and SFR camera operation.

The magnitude of the concavity of the wall from which the shock is reflected is characterized by the dimensionless parameter h/R, where h is the height and R the radius of a spherical segment (see Fig. 1). A series of experiments was performed in which h/R varied between 0.1 and 0.9.

The geometry of the experiment excludes the possibility of obtaining shadow photographs of individual instants of the flow picture, as had been done in [1]; however, the similarity of the x vs t diagram in any case permits a qualitative representation of the flow picture (Fig. 2) in the experiments described below. In the case $h/R \geq 0.5$, the shock being reflected from the bottom of the segment acquires the spherical shape r_1 (Fig. 2a). The cumulative effect originates upon collapse of the cylindrical transverse wave w on the tube axis, and the transverse wave originates under the effect of a stream of substance sliding along the segment walls toward the center. This stream appears during reflection of an incident wave on the sloping walls of the spherical

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Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 4, pp. 33-37, July-August, 1976. Original article submitted August 27, 1975.