THE MICROARC OPERATING REGIME OF MHD GENERATOR ELECTRODES

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The preliminary results of an investigation of the operation of MHD generator electrodes at relatively high current densities are reported. The experiments were conducted in the channel of a MHD generator, driven by combustion products, with both cooled metal and silicon carbide electrodes. Observation and photographs of the electrodes revealed that at sufficiently high currents microarcs appear at the electrode surface. The phenomenological aspects of arc behavior under conditions characteristic of MHD generator operation are examined. The electrode-insulator interface has an important influence on arc behavior, as does the film of potassium compounds deposited on the electrode surface. These characteristics of the microarcs may be of considerable significance in relation to electrode erosion processes.

In tests on a U-02 MHD generator with cooled metal electrodes we obtained currents difficult to explain in terms of thermionic emission from the electrode surface, even in the case of formation of a potassium film. Thus, in the short-circuit regime the current from the electrode pair reached 12 A, which corresponds to a mean current density of more than 1 A/cm^2 at a metal surface temperature of 870-950° K. Visual observations and photographs of the electrodes showed that at these current densities small bright spots appear on the electrode surface. These spots constitute microarcs, by means of which the plasma makes contact with the electrodes through the cold, poorly conducting boundary leyer.

The presence of similar spots was reported in [1, 2]. The behavior of the microarcs was later described in greater detail in [3, 5]. We have now made a full-scale qualitative study of the microarcs burning at the cathode surface in a MHD generator channel.

The generator operated on natural gas combustion products seeded with potash in amounts up to 1 mol.-% with respect to potassium concentration. We investigated water-cooled electrodes made of 1 Cr18Ni10Ti stainless steel and electrodes made of silicon carbide (SiC) plus small amounts of refractory metals (Ti, Mo or Nb).

The rectangular MHD channels were 65-80 mm high and 220-270 mm wide. The generator had segmented electrodes. The investigation and visual observations of the microarcs were made on electrode pairs located 200 mm from the point at which the flow entered the magnetic field for the metal and 500 mm for the SiC electrodes. The electrodes were rectangular, the height of the electrode being equal to the height of the channel. The metal electrodes were 18 mm and the SiC electrodes 30 mm wide. The insulation gaps between the electrodes were 15 mm and 20 mm wide, respectively. The insulators between the metal electrodes consisted of sheets of dense aluminum or magnesium oxide and an aluminum oxide coating 0.5-0.8 mm thick deposited by gas-flame atomization on cooled metal spacers. High-alumina concrete served as insulation between the silicon carbide electrodes.

Subsequently, we introduced into the channel a water-cooled circular stainless-steel electrode 20 mm in diameter, which enabled us to observe and photograph the entire surface of the electrode and the adjacent parts of the interelectrode insulation.

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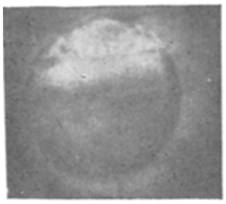

Fig. 1

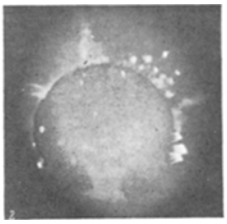

Fig. 2

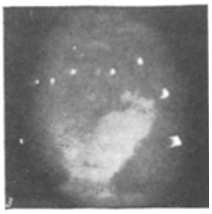

Fig. 3

The plasma flow in the channel was subsonic, the flow velocity in different experiments varied from 400 to 650 m/sec at channel pressures of 0.60-0.73 bar. The temperature in the flow core was measured by spectral line inversion and varied from 2150° K to 2300° K in the oxygen enrichment regimes. For the above-mentioned flow parameters the metal electrode temperature was 770-820° K under normal conditions and 870-950° K in the oxygen enrichment regimes; the corresponding temperatures of the silicon carbide electrodes were 1480-1520° K and 1920-1980° K.

The electrode surface temperature was determined by means of thermocouples embedded in the electrode, the correction for the depth of imbedment of the junction was determined from the measured heat flux density. The surface temperature of the SiC electrodes was determined optically with a OPPIR-017 optical pyrometer aimed at the electrode surface through the plasma flow. Moreover, the electrode temperature was measured at distances of 5-7 mm from the surface washed by the gas. For this purpose we employed a OMP-49 optical micropyrometer, which was aimed at the bottom of a hole formed in the electrode.

In the experiments we measured the electrical characteristics of the segmented generator for simultaneous stepwise variation of the load on all the electrode pairs; moreover, we measured the smooth current-voltage characteristics of an individual electrode pair with the other pairs disconnected. These characteristics were recorded by a PDS-01 two-coordinate recording potentiometer. Furthermore, by means of a series of probes mounted in the insulating wall we measured the potential distribution between the anode and cathode of the investigated electrode pair. Oscillograms were obtained for the variable component of the current, the voltage, and the potential difference between the cathode and the nearest probe. Visual observations of the electrode surface were made through special openings in the anode, which were also used in obtaining photographs. In order to increase the arc observation angle we used a special lens with focal length F = 400 mm located inside the magnet 900 mm from the electrode. The photographs were obtained with a "Zenit-3M" camera ("Gelios-44" lens) on black-and-white and reversible color film with speeds of 250 and 22 (Soviet standard units), respectively, at exposures from 1/125 to 1/250 and f = 2. Films were obtained with "Kvarts" and "Lida" motion-picture cameras on black-and-white and reversible color film with speeds of 45 and 22 (Soviet standard units), respectively, at a filming speed of 48 frames per second.

In the oxygen enrichment regimes we observed a considerable increase in the luminosity of the flow and the walls as compared with normal conditions. The flow becomes less transparent and the sharpness of the electrode image deteriorates: the contours of the areas of deposition of the thin film of potassium compounds, the edge of the electrode, and other details of the electrode surface, clearly distinguishable under normal conditions (Fig. 1), become less obvious. The contrast of the image of the microarcs in the black-and-white photographs is sharply reduced, although the microarcs are still quite clearly observable to the eye.

In the oxygen enrichment regimes the microarcs on the metal cathodes were usually easily distinguishable at currents of 5-6 A (electrode area 11 cm^2). These currents were reached near the short-circuit regime. However, microarcs could also be observed at much lower currents. The photographs of the microarcs at the surface of a circular metal electrode (d = 25 mm) presented in Figs. 2 and 3 were obtained at currents of the order 2 A and 1 A, respectively. The arcs were visible as bright white moving spots with a characteristic rainbowlike aureole. Microarcs were observed chiefly around the edges of the electrode and much less frequently nearer to the center. Several microarcs were observed simultaneously (up to 5-6 depending on the current). The observed rate of displacement of the microarcs was small (about 0.5-1 cm/sec); the luminous region of the arcs measured 1-2 mm.

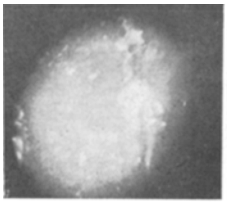

Fig. 4

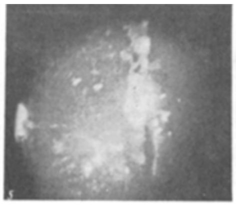

Fig. 5

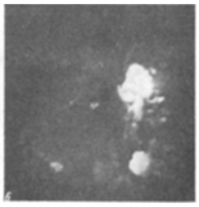

Fig. 6

At a relatively low plasma conductivity in normal regimes the range of investigation is extremely limited with respect to currents by the induced $u \times B$ field. Much larger currents at low plasma conductivity can be obtained in the "braking" regime, when the direction of the external field conforms with the direction of the induced field. The use of this method made possible a considerable extension of the range of investigation with respect to current and other parameters, without affecting the channel operating conditions.

Thanks to the presence of a magnetic field, in these experiments the conditions of development of the microarcs remained close to the actual operating conditions of the MHD generator. As observations showed, externally the behavior of the arcs in the strictly generator regime differs little from their behavior in the "braking" regime. This confirms the essential similarity of the conditions of existence of microarcs in both regimes, since, obviously, the plasma potential distribution in the electrode regions and the behavior of the arcs depend only on the magnitude and direction of the current and the magnetic induction. The experimental conditions differed from those described in [3, 5] chiefly with respect to the presence of a magnetic field. The effect of the magnetic field on the bahavior of the arcs is expressed, in particular, in their rates of displacement in connection with the interaction of the current and the magnetic field. The redistribution of current density in the regions of Hall-effect diffusion flow also plays a certain part.

The magnetic induction was varied from 0 to 1.8 Wb/m^2 and the current from 0 to 25 A, which corresponds to a current density of 2-2.5 A/cm^2; microarcs appeared on the metal electrodes at currents of 2-2.5 A. The microarcs burned stably at currents of about 4-5 A. It is characteristic that the currents at which the microarcs appeared and the minimum currents at which they burned stably were approximately the same for a circular metal electrode with a smaller area and the rectangular electrodes. Arcs also appeared at approximately the same currents on the SiC electrodes.

It is interesting to note that the most intense arcs burn characteristically at the boundary between the cathode and the insulator behind it. Usually it was possible to distinguish a single arc of maximum brightness, which moved vertically along the edge of the cathode at the interface with the insulation (Fig. 4). The rate of displacement of these arcs along the edges, as far as can be judged from visual observations, was 2-3 mm/sec. With further increase in the current cathode spots also appear at the leading edge of the electrode, but these are smaller than the spots further downstream (Fig. 5). As the current increased, so did the size and brightness of the arcs, and a greater number of arcs appeared at the edge (Fig. 6). When the current was switched off, the microarcs disappeared, reappearing at the same characteristic points when the experiments were repeated.

The film of potash and other potassium compounds deposited on the surface of the electrode plays a very interesting role. As observations showed, the microarcs usually burn in the areas where the film is

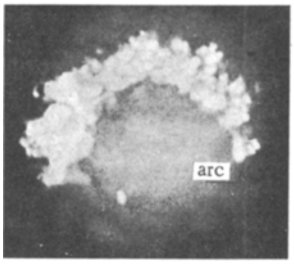

Fig 7

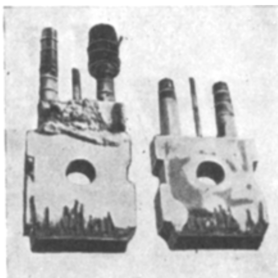

Fig. 8

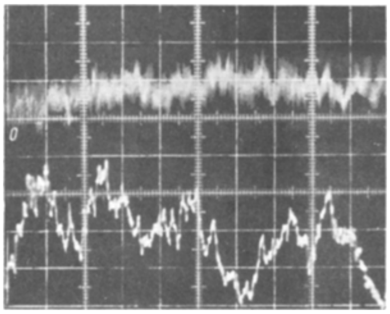

Fig. 9

deposited. In the experiments with a circular electrode arcs burned simultaneously at several points near the edge of the electrode, where the potash film was hottest (Fig. 7). The areas coated with a potash film had high temperatures and accordingly high luminosity (in the figure the extensive luminous region at the top). Observation showed that the arcs may burn not only at the surface of the electrode but also at the surface of the insulator near the edge of the electrode at points where the insulator is covered with a potash film, the latter apparently creating an electrical current between the spot and the electrode.

The tendency of the microarcs to burn on the film or at its edge can probably be attributed chiefly to the higher temperature of the film surface and its relatively low thermal conductivity. At a low film thermal conductivity the rate of displacement of the spots may be much higher [6], and because of the roughness of the film the conditions may be favorable for field emission. The cathode spots on such films more closely resemble spots of the first type (according to the classification proposed in [6]) and should cause less erosion of the cathode material.

As the magnetic field increases from 0 to 1.8 Wb/m^2 at a fixed applied voltage, a considerable increase in the number and instability of the cathode spots was visually observed, although the current varied only slightly (approximately by 20%). The small variation of the current is probably attributable to an increase in the Hall parameter and a decrease in the efficiency of plasma conduction with a simultaneous increase in the induced emf resulting in a high degree of mutual compensation.

In the experiments with metal electrodes the arcs at the boundaries between the electrode and the insulator penetrated into the gap between the electrode and insulator surfaces. These arcs burned at some distance from the electrode surface exposed to the flow and were quite stable. An inspection of the channel with metal electrodes revealed that at the points where cathode spots were most frequently observed there were traces of electrode melting and congealed slga formation. On the lateral surfaces of the cathode, just as on the adjacent lateral surface of the insulator, the coating had been corroded by the arcs and irregular zigzag-shaped craters were observed; since the gap between the surfaces was very small, the coating was symmetrically corroded on both sides (Fig. 8). In the case of a circular metal electrode surrounded by dense aluminum oxide, insulation arcs were also observed to burn in the gap between the electrode and the insulator, a process accompanied by local melting of the cathode with the formation of characterisic traces on the surface of the metal and the adjacent insulator.

As already mentioned, we measured the potential distribution of probes located between the anodes and the cathodes of the investigated metal electrode pairs. As the current increases from 0 to 4-6 A at $B = 1.8$ Wb/m^2, the potential difference between the cathode and the nearest probe, about 10 mm away, increases from 10-20 to 100-130 eV. Obviously, this potential difference is composed of the true cathode drop near the spot, the drop in the constricted arc resting on the spot, and the drop in the plasma layer, where the current flow may already be assumed to be diffusional. According to the existing data (for example, [7]), the cathode drop for copper and iron cathodes is 15-16 V, and for a sodium cathode 5-9 V, i.e., the true cathode drop evidently forms a small part of the total drop in the electrode region.

The probe measurement of electrode potential drops in microarc regimes is complicated by the fact that the potential difference between the probe and the electrode obviously depends on the relative position of the probe and the nearest microarcs. As a result of the motion of the microarcs over the surface of the electrode this relationship constantly changes. The variable component of the cathode drop has a range of 5-7 V and a frequency of the order of 3-6 kHz (Fig. 9). Oscillograms of the variable components of the current $I_{\sim}$ (upper curve) and cathode voltage drop $\Delta V_{k\sim}$ at a steel electrode in the channel of a MHD generator operating in the generator regime are presented in Fig. 9; the constant current is equal to 1 A. The scales of the oscillograms are as follows: current 0.36 A/cm, cathode voltage drop 3 V/cm, time 1 msec/cm (one division on the photograph corresponds to 1 cm).

It may be assumed that this frequency is caused by the periodic quenching and reappearance of the microarcs at a new site.

In conclusion it should be noted that the experiments indicate the possibility of considerable erosion of cold electrodes in the presence of microarcs on the surface. Erosion may be reduced by the rapid motion of the spots under the influence of a magnetic field and the flow. A film of potash and other potassium compounds on the surface of the electrode may play a certain protective role, since in a MHD generator channel the rate of deposition of potash on the cathode and its average rate of removal in the cathode spots, referred to the total surface of the electrode, may be commensurable. Arcs burning between the electrode and the interelectrode insulator, where the motion of the arcs is impeded and their destructive effect most intense, are especially dangerous. The designer should take steps to counteract this effect.

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