INVESTIGATING THE REMOVAL OF HEAT AT THE CATHODE SPOT OF AN INTENSIVELY SWEPT ELECTRIC ARC

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We describe the installation and method for a study of the transfer of heat in the near-electrode region of an intensively swept electric arc. We present the experimental data demonstrating the relationship between the heat removed from the cathode spot and the current strength for an air flow rate of 6.6 g/sec (the air supplied to the plasmotron chamber) and with an external magnetic field exhibiting a strength of 850 Oe.

The heat transfer in the near-electrode region of an intensively swept electric arc was carried out on a coaxial segmented 200 kW plasmotron. The manner in which the plasmotron was designed made it possible, on the basis of measurement results, to determine the fraction of heat that reaches the electrode from the near-electrode region of the arc.

A diagram of the plasmotron is shown in Fig. 1. The electrode chamber is made in the form of a cylindrical tube which consists of electrically insulated segments. The internal electrode and all of the chamber segments have been fabricated of copper and are cooled with water. To reduce electrode erosion and to maintain stable burning of the arc, air is fed in tangentially. It is for precisely this purpose that two series-connected coils have been included, and their total magnetic field, calculated according to the data of [2], depending on the distance between their centers, varies from 36.5 I_{Oe} to 71 I_{Oe}.

The plasmotron is powered by a mercury rectifier with a minimum voltage of 825 V. A liquid rheostat is series-connected to the plasmotron, and its purpose is to provide for a smooth current change within the circuit. The voltage and current are recorded by means of an automatic NZ40 voltmeter and an automatic NZ75 ammeter.

The temperature of the water in the electrodes was measured with the Chromel–Copel thermocouples of the automatic electronic ÉPP-09MZ potentiometers.

The coils were supplied from a dc 220V generator. The current was varied from 15 to 50 A by means of a wire rheostat connected into the coil circuit. The current in the coil circuit was recorded with an M-106 ammeter.

Air was used as the working gas and it flowed at a rate of 6.6 g/sec in this series of experiments.

Atmospheric pressure prevailed within the plasmotron chamber. The overall water flow rate was 0.5 liter/sec.

It became apparent during the course of the plasmotron adjustment that the arc burns stably in a current range of 100-1500 A (no tests were carried out at higher currents).

Prolonged plasmotron operation was not required during these experiments, so that it was turned on for 60 sec. During the course of the adjustment tests, the plasmotron power was varied from 30 to 200 kW.

We carried out tests to determine the heat removed through the cathode spot of the intensively swept electric arc; this was done on the above-described plasmotron in a current range of 100-800 A.

The voltage was applied to the internal electrode (the anode) and to one of the segments of the external electrode (the cathode). Thus the cathode spot moved along only a single segment – along the cathode.

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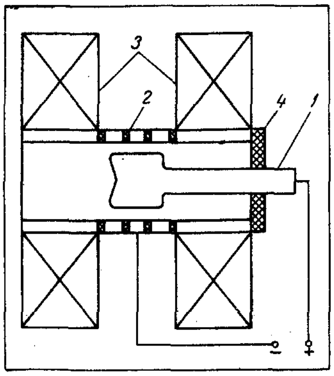

Fig. 1

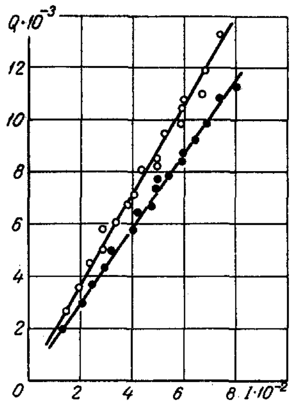

Fig. 2

Fig. 1. Coaxial segmented plasmotron: 1) inner electrode; 2) segmented chamber; 3) electromagnetic coils; 4) insulator.

Fig. 2. Heat removed to cathode versus current: ●) h = 5 mm; O) 7.

The tests were carried out with segments of equal height (5-8 mm); this was done so as to calculate the heat removed to the electrode through the cathode spot.

All of the heat removed to the cathode is made up of the following components: the convection and radiation Q_{cr}, the heat Q_s removed through the cathode spot, and the Joule heat Q_J liberated within the cathode; the total heat flow to the cathode is represented by the sum

$$Q = Q_{cr} + Q_s + Q_J \tag{1}$$

The Joule heat for the current I can be determined from the formula

$$Q_J = I^2 R, \tag{2}$$

with R, in this case, denoting the resistance that is a function of the cathode-spot dimensions, as well as of the temperature and dimensions of the electrode. We know from [4] that R can be calculated with the formula

$$R = \frac{\rho}{4r_0}, \tag{3}$$

where r_0 is the radius of the cathode spot under the assumption that the arc spot is circular in shape.

In conjunction with (3) we derive the expression for the Joule heat:

$$Q_J = \frac{I^2 \rho}{4r_0}. \tag{4}$$

For a current of 1000 A, r_0 = 0.1 cm and $\rho = 9.89 \cdot 10^{-6}\ \Omega \cdot$cm for copper [1, 3] (at the melting point) the Joule heat amounts to 0.2% of the total heat flow to the cathode, so it can therefore be neglected.

If the quantity of convection and radiation heat per unit of segment length is denoted q_{cr} and if the segment height is denoted h, for the total convection and radiation flow Q_{cr} we derive the expression

$$Q_{cr} = hq_{cr} \tag{5}$$

The quantity of heat removed to the electrode through the cathode spot is naturally independent of the height of the cooled segment. The total heat removed to segments of various heights will differ only in terms of the convection and radiation components of the heat flow.

Bearing this circumstance in mind and considering formula (5), by measuring the total heat flow at two or more segments of various heights we can determine the heat removed through the cathode spot of an electric arc.

Indeed, having completed the sequence of experiments on two segments whose heights are h_1 and h_2 (let $h_2 > h_1$), we obtain, respectively, the two functions $Q_1(I)$ and $Q_2(I)$. Keeping in mind formulas (1) and (5), as well as the fact that we neglect the Joule heat, we can write

$$Q_1(I) = h_1 q_{cr}(I) + Q_s(I),$$
$$Q_2(I) = h_2 q_{cr}(I) + Q_s(I). \tag{6}$$

From the system of equations (6) we obtain the values for the heat flow in the cathode spot, and for the convection and radiation flows removed to the cathode:

$$q_{cr}(I) = \frac{Q_2(I) - Q_1(I)}{h_2 - h_1}, \tag{7}$$

$$Q_s(I) = \frac{h_2 Q_1(I) - h_1 Q_2(I)}{h_2 - h_1}. \tag{8}$$

The quantity of the heat removed through the cathode spot per second per unit current is referred to as the volt equivalent of heat loss (of heat removal) and is denoted:

$$\Delta U_c^* = \frac{Q_s(I)}{I}. \tag{9}$$

Considering formulas (8) and (9), we obtain the expression for the volt equivalent:

$$\Delta U_c^* = \frac{h_2 Q_1(I) - h_1 Q_2(I)}{I(h_2 - h_1)}. \tag{10}$$

This method can also be applied to the determination of the flow of heat removed through the anode spot and, consequently, to determine the volt equivalent of the heat losses through the anode spot.

The experiments to determine the removal of heat through the cathode spot and its volt equivalent were carried out for a current range of 100-800 A for an air flow rate of 6.6 g/sec.

The results of the experiment are shown in Fig. 2. We see from the figure that in the current range of 100-800 A the relationship between the total heat removed to the segment and the current can be regarded as linear. Thus for the segments of heights h_1 and h_2 in this range of currents we can write the total heat flows in the form

$$Q_1(I) = k_1 I; \quad Q_2 = k_2 I. \tag{11}$$

The corresponding formulas for $Q_s(I)$, $q_{cr}(I)$, and ΔU_c^* have the form:

$$Q_s(I) = \frac{h_2 k_1 - h_1 k_2}{h_2 - h_1} I, \tag{12}$$

$$q_{cr}(I) = \frac{k_2 - k_1}{h_2 - h_1} I, \tag{13}$$

$$\Delta U_c^* = \frac{h_2 k_1 - h_1 k_2}{h_2 - h_1}. \tag{14}$$

Here k_1 and k_2 are the angular coefficients of the respective functions for segments h_1 and h_2. We calculated the values of k_1 and k_2 by the method of least squares [5]:

$$k = \frac{\sum_{i=1}^{n} Q_i I_i}{\sum_{i=1}^{n} I_i^2}, \tag{15}$$

but $Q_i = 4.18\sigma\Delta t_i$, so that

$$k = \frac{4.18\,\sigma \sum_{i=1}^{n} I_i \Delta t_i}{\sum_{i=1}^{n} I_i^2}, \tag{16}$$

where Δt_i is the temperature increment in the i-th experiment; σ is the water flow rate; I_i is the current in the i-th experiment.

It should be noted that for currents $I > 600$ A and for limited air flow rates the heat flow to the cathode as a function of the current deviates from the linear, while for air flow rates of 6.6 g/sec the linearity is retained to 800 A.

The intensity of the external magnetic field in the arc combustion zone in each of the experiments amounted to 850 Oe; air was fed tangentially into the discharge chamber so that the directions of the magnetic and gasdynamic forces acting on the arc coincided.

Thus a cocurrent magnetogasdynamic rotation of the arc was achieved in the plasmotron at atmospheric pressure in the discharge chamber.

In the experiment carried out at an air flow rate of 6.6 g/sec (Fig. 2) we obtained the following relationships:

for segments of height $h_1 = 5$ mm

$$Q_1(I) = 14.23I, \tag{17}$$

for segments of height $h_2 = 7$ mm

$$\begin{aligned} Q_2(I) &= 16.80I, \\ q_{cr}(I) &= 1.28I. \end{aligned} \tag{18}$$

The heat flow through the cathode spot, calculated according to (12), amounts to

$$Q_s(I) = 6.52I. \tag{19}$$

The heat flows are expressed in watts. The volt equivalent of the heat losses in the cathode spot amounted to 6.52 V.

It has thus been demonstrated experimentally that the heat removed to the electrode through the cathode spot of the intensively swept arc of a plasmotron in the current range of 100-800 A is a linear function of the current.

NOTATION

Q is the heat removed to the cathode;
$Q_{c,r}$ is the convective and radiant heat flow;
Q_J is the Joule heat;
Q_s is the heat removed through the cathode spot;
ΔU_c^* is the volt equivalent;
I is the current strength;
r_0 is the radius of the cathode spot;
ρ is the specific resistance
h is the segment height.

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