HEAT EXCHANGE IN THE CATHODE SPOT OF AN ELECTRIC ARC IN AN ARGON MEDIUM

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The dependence of heat removal through a cathode spot on the current, magnetic induction in the circular gap, and the argon flow rate is studied.

The study of heat exchange in the discharge chamber of an electric arc gas heater is of considerable interest both from the applied aspect in the search for means of increasing the durability, reliability, and efficiency of arc gas heaters, and from the theoretical point of view for the accumulation of experimental material which can be used for a quantitative comparison of theory with experiment. This applies particularly to the electrode regions of an electric arc, for which there does not yet exist a complete theory able to explain all the aspects of the complicated processes occurring in them.

The present article is devoted to a discussion and description of the results of experimental studies of heat exchange in the cathode spot of an electric arc of constant current, moving under the influence of electromagnetic and gas dynamic forces in an argon medium at atmospheric pressure.

The study was conducted on an electric arc preheater of a coaxial design having water-cooled copper electrodes [1]. An electric control circuit using the current of solenoids in power thyristors was used for smooth and stepped variation in the magnetic field strength in the circular gap.

The determination of heat fluxes in the arc spot was conducted by a method used in [1-3]. The essence of the method consists in the measurement of heat fluxes into circular cathode sections of different widths. Here it is assumed that the heat flux through the cathode spot does not depend on the width of the section, while the convective and radiative components are proportional to the width of the section.

For two sections of different widths 1 and 2 the heat flux through the cathode spot is determined from the equation

$$Q_s = \frac{\delta_2 Q_1 - \delta_1 Q_2}{\delta_2 - \delta_1}, \tag{1}$$

while the convective and radiative components per unit section length are given in total by

$$q_{cr} = \frac{Q_2 - Q_1}{\delta_2 - \delta_1}. \tag{2}$$

The total heat fluxes in sections of different thicknesses depend on the mode of operation of the apparatus and in particular on the gas flow rate, the induction of the external magnetic field, and on the conditions of cathode cooling.

However, a case where Q is proportional to I is often possible in some range of current variation. Then

$$Q = kI. \tag{3}$$

An analogous situation also occurs with respect to the heat flux at the spot

$$Q_s = \Delta U_c^* I. \tag{4}$$

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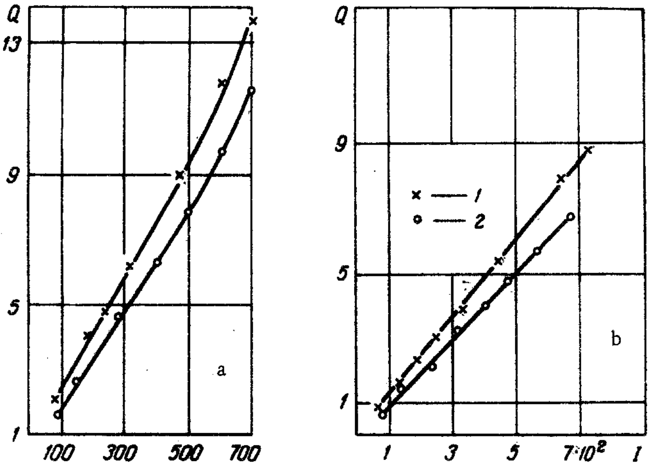

Fig. 1. Dependence of total heat loss into cathode on the current at a magnetic induction in the gap of B = 0.174 T and argon flow rates G = 1 g/sec (a) and G = 1.7 g/sec (b): 1) section width 7 mm; 2) 5 mm. Q, kW; I, A.

The quantity $\Delta U_c{}^*$ is usually called the volt equivalent of the heat flux through the cathode spot.

Using (1)-(4), an equation can be obtained for the volt equivalent

$$\Delta U_c^* = \frac{\delta_2 k_1 - \delta_1 k_2}{\delta_2 - \delta_1}. \tag{5}$$

In the present work the widths of the sections were taken as $\delta_1 = 5$ mm and $\delta_2 = 7$ mm. The heat fluxes were determined by calorimetry of water, the temperature of which was determined with automatically balanced bridges of 0.5 class precision with copper resistance thermometers of K-P class precision having a deviation from the standard graduation of 23 (GOST 6651-59), equal to $\Delta t = \pm(0.3\text{-}3.5 \cdot 10^{-3}\,[t])$ °C.

The measurements were conducted on cathode sections of different widths, for which the difference in width of the two rings was 40% of the narrow ring, which is considerably greater than the total error of the indirect heat flux measurements which did not exceed 10%. This makes it possible to determine reliably enough the heat flux through the cathode spot while not causing a significant difference in q_{cr} due to a large difference in the widths of the sections.

In the experiments conducted the geometrical dimensions of the components of the discharge chamber of the arc heater were constructed with a precision of ±0.01 mm. The outer electrode (cathode) diameter was 40 mm, while the inner (anode) diameter was 28 mm. Argon was supplied tangentially to the discharge chamber in such a way that the electromagnetic and gas-dynamic forces were opposed.

During the course of the experiment the arc current varied from 50 to 750 A and the external magnetic field strength from 0.1 to 0.25 T. The relative reduced error in the measurements of these values did not exceed ±1.5%. The experiments were conducted at three argon flow rates: g = 0.4, 1, and 1.7 g/sec. Some results of the measurements of total heat fluxes into the section-cathodes are presented in Fig. 1. It is seen from Fig. 1 that for argon flow rates of 1 and 1.7 g/sec the dependence of the total heat fluxes into a section on the current is well approximated by the expression $Q_c = aI + B$. It deviates significantly from linear for an argon flow rate of 0.4 g/sec, and for currents of 200-500 A the experimental points lie satisfactorily along a parabola. Proceeding from approximation equations obtained by the method of least squares, the heat loss through the cathode spot at different values of the external magnetic field induction was calculated from Eq. (1).

The dependence of the heat loss into the cathode spot $Q_s = f(B)$ at currents of 100 and 400 A for three argon flow rates is presented in Fig. 2. The dependence shown for a flow rate of 1 g/sec has a maximum. Its presence can be explained by the initial improvement in the conditions of heat loss from the cathode spot with an increase in the external magnetic field (i.e., the rotation rate of the arc). With a further increase in the field the movement of the discharge reaches a velocity at which the temperature of the cathode in front of the moving spot increases because of its travel along its path. This leads to a decline in the heat loss from the spot.

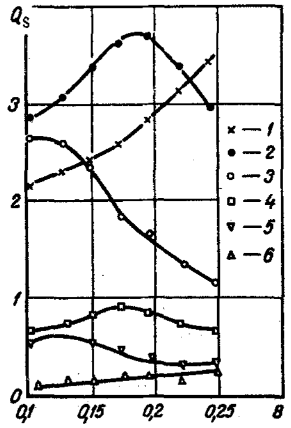

Fig. 2. Heat loss into cathode spot as a function of the external magnetic field for arc currents of I = 100 and 400 A at three argon flow rates G = 0.4, 1, and 1.7 g/sec: 1) G = 0.4 g/sec, I = 400 A; 2) 1.0 and 400, respectively; 3) 1.7 and 400; 4) 1.0 and 100; 5) 1.7 and 100; 6) 0.4 and 100. Q_s, kW; B, T.

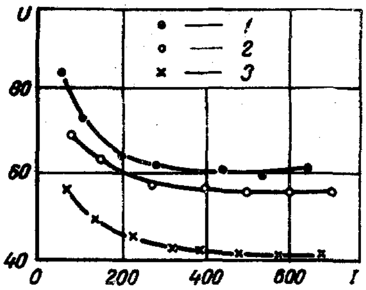

Fig. 3. Dependence of arc voltage on current and argon flow rate for B = 0.174 T and G = 0.4, 1.0, and 1.7 g/sec: 1) G = 0.4 g/sec; 2) 1.0; 3) 1.7. U, V; I, A.

The results of the determination of heat fluxes into the cathode spot are different for argon flow rates of 0.4 and 1.7 g/sec from those at a flow rate of 1 g/sec. In the first case the dependence $Q_s = f(B)$ has an increasing nature, in the second it has a decreasing nature, although the general dependence is not of a random nature and creates the impression that an extremum may be reached in both cases. Such behavior of the curves can be explained by the effect of the flow rate of the working gas on the rotation rate of the arc, which for an argon flow rate of 0.4 g/sec (within the range of variation in the magnetic induction B studied) is still not sufficient to obtain the optimum specific heat loss from the spot, while for an argon flow rate of 1.7 g/sec it is already high enough that it leads to a decrease in heat flux through the cathode spot. This, from all appearances, with the opposing effect of the gas-dynamic and electromagnetic forces, an increase in the flow rate of the working gas leads to a growth in the rotation rate of the arc under the given conditions. As a basis for such a hypothesis we take into account the column form of the arc discharge, which for an arc burning in a coaxial heater under the influence of an external magnetic field is close to evolvent. An increase in the argon flow rate leads to a straightening of the discharge column, making its position approximately radial, since in our case the gas-dynamic force is opposite in direction to the electromagnetic force. As a result the tangential component of the Ampere force exerted per unit length of the cathode surface increases, and so does the velocity of rotation of the arc, since the velocity is determined by just this component of the force.

The discussion given above is confirmed in some measure by the decreasing nature of the dependence of the arc voltage on the flow rate of the working gas (Fig. 3), since a decrease in the length of the discharge occurs along with its straightening.

If it is assumed that the maximum heat flux through the cathode spot (Fig. 2) corresponds to almost complete heat loss of the power supplied to the cathode area of the arc (Q_{ca}), then one can evaluate ($\Delta U_c - \varphi$) from Eq. (4); evidently it will be somewhat understated.

For a flow rate of 1 g/sec Ar, ($\Delta U_c - \varphi$) has a value of 9.3 V, which is considerably lower than the ionization potential of argon ($E_i = 15.76$ V), but higher than the ionization potential of copper ($E_i = 7.72$ V) [4]. It is evident that near the cathode the argon arc burns mainly in vapors of the electrode material.

NOTATION

Q	is the heat flux;
I	is the current strength;
k	is the coefficient of angular dependence;

G is the mass flow rate of gas;
ΔU_c^* is the volt equivalent of heat losses in the cathode;
ΔU_c is the potential drop at the cathode;
δ is the width of the cathode section;
φ is the work potential of the output;
Δt is the absolute error, in °C;
$[t]$ is the absolute temperature, °C.

Subscripts

1, 2 denote sections of different width and the values corresponding to them;
s denotes values corresponding to the cathode spot;
cr denotes the convective–radiative component;
c denotes values refered to the cathode;
$*$ denotes volt equivalent.

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