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CURRENT AND HEAT FLOW DENSITY ON THE ANODE OF A PLASMATRON WITH RECIPROCAL POLARITY

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UDC 537.525

Current and heat flow density to the end electrode of a plasmatron were measured with different currents and flow rates of argon.

Physical processes in the regions near the electrodes of the electric arc of plasmatrons determine their thermal efficiency and life. Many works deal with the investigation of the physical properties of the electric arc and the processes occurring near the electrodes; an entensive bibliography of these works is contained in [1, 2]. The authors of [3-5] present the results of measurement of the local parameters of the arc spot with a sectional electrode that scans the arc column perpendicularly to its axis. However, we do not know of any work that contains the results of measurement of the current and heat flow density in the end electrode of a plasmatron.

The present work contains an attempt to devise a direct action plasmatron with sectional end electrode, and to measure the current and heat flow density in the spot of the electric arc. The sensor for measuring the current and heat flow density to the end electrode is a direct action plasmatron with sectional end electrode (Fig. 1). The end electrode is made of two water-cooled copper sections which touch each other but are thermally and electrically insulated; each section has a working surface of 1.5 × 1.5 cm. The heat and electrical insulator is mica, 0.1 mm thick. The two sections of the end electrode are fastened to each other and can be shifted inside the plasmatron perpendicularly to their interface on the flat surface of the insulator of fabric glass laminate which is 2-3 mm thick, has in the center a circular opening of 10-mm diameter, and covers the plasmatron nozzle of 5-mm diameter. On its inner side the flat insulator has grooves milled tangentially to the opening for the supply of stabilizing gas. After the sectional copper electrode is assembled, it is carefully ground. Grinding of the electrode has two objects. Firstly, to prevent its erosion in operation, and secondly, to prevent leakage of the stabilizing gas between the electrode and the insulator. The newly devised direct action plasmatron with sectional end electrode makes it possible to measure the current and heat flow density in the spot of the electric arc with convective flows minimally affecting the arc and the spot. For the sake of brevity we will call the newly devised installation a PSE, plasmatron with sectional electrode.

Dnepropetrovsk Metallurgical Institute. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 43, No. 1, pp. 104-109, July, 1982. Original article submitted November 21, 1980.

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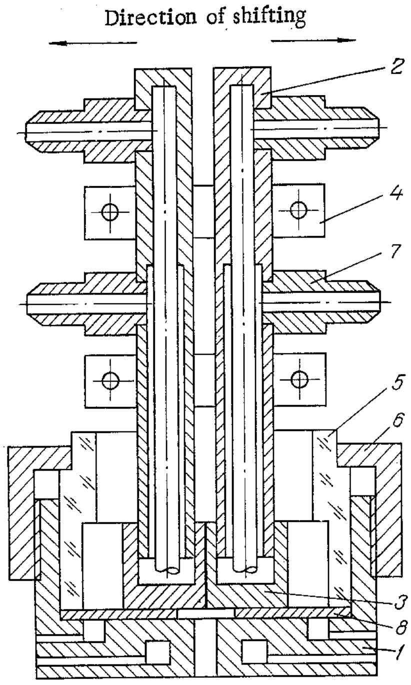

Fig. 1. Plasmatron with sectional electrode (PSE): 1) PSE housing; 2) sectional electrode; 3) electrodes; 4, 5) insulator; 6) lid of the plasmatron; 7) nozzles for mains connection and cooling water supply; 8) insulator of fabric glass laminate with tangential openings for gas.

For measuring the current and heat flow density with the aid of a PSE, we worked out an arrangement which, in general form, is shown in Fig. 2. The PSE 1 is firmly mounted above the water-cooled electrode 3 at a distance of 20 mm from its surface. Each section of the end electrode receives through shunts and a smoothing filter its voltage and cooling water whose flow rate and temperature are measured by instruments 4, 5. Joined to the sectional electrode is the shifting mechanism (not shown in the diagram) which drives it at a speed of $8.4 \cdot 10^{-5}$ m/sec. After the PSE has attained its working regime, the shifting mechanism moves the sectional electrode over the surface of the insulator with constant speed, and all parameters are recorded with the aid of the oscillograph N-115. While the electrode is shifted, changes of the heat flow and current to the section are measured, and in the extreme position a microswitch switches off the shifting mechanism and the electric arc, and the experiment ends. In consequence of the finite magnitude of the heat capacity of the sectional electrode there is always some lag of the measured values behind the true values [6]. The solution of the equation of the heat balance with known assumptions [7] yields a differential equation which correlates the temperature of the sensor T_q with the measured temperature T_u:

$$\frac{dT_q}{dt} + \frac{1}{\tau}(T_q - T_u) = 0. \tag{1}$$

From this equation we can easily obtain the speed with which the interface of the PSE sections moves:

$$v \leqslant \frac{\mu}{1-\mu} \frac{1}{\tau} \frac{T_q}{dT_q/dx}. \tag{2}$$

For determining the speed of the sectional electrode at which the error in measuring the heat flow does not exceed μ, it suffices to determine τ and the nature of the change of $T_q(x)$. Then on the curve $T_q(x)$ we choose the minimum value of dT_q/dx and find v.

When the anode spot is shifted through Δx across the boundary of the sectional electrode, the current and heat flow over the surface $\Delta S = \Delta x \Delta y$ of segment S are summed:

$$Q_q = \sum_{i=1}^{n} \sum_{l=1}^{k} q(x_i y_l) \Delta x_i \Delta y_l. \tag{3}$$

In the limit transition, when the smallest of the elements tends to zero,

$$Q = \int_x^R dx \int_0^{\sqrt{R^2-x^2}} q(x, y) dy. \tag{4}$$

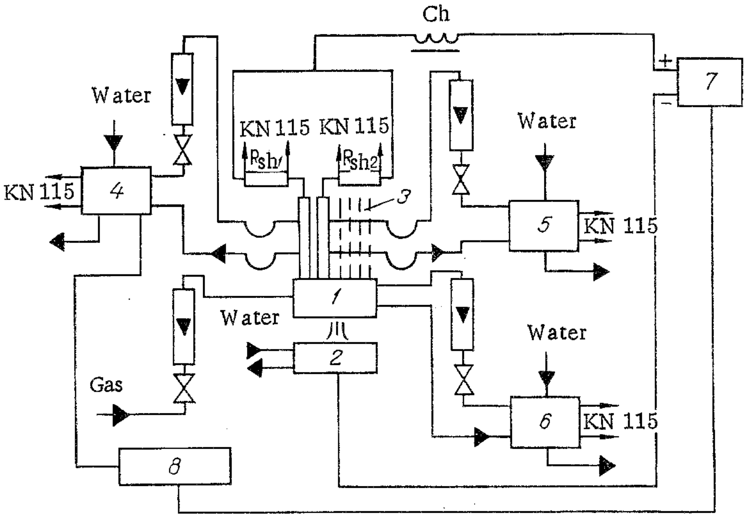

Fig. 2. Diagram of the electrical and calorimetric measurements of the PSE: 1) PSE; 2) water-cooled electrode; 3) sectional electrode; 4, 5, 6) instruments for measuring the rise of the water temperature; 7) power supply source with descending volt—ampere characteristic; 8) unit for electrical and heat protection; Ch) smoothing filter (choke coil).

After differentiation of the double integral with respect to the variable x

$$\frac{dQ}{dx} = -2\int_{0}^{\sqrt{R^2-x^2}} q(x,\ y)\,dy. \tag{5}$$

If we introduce the new variable r and assume that the distribution of the specific heat flow in the spot of the electric arc is axisymmetric, we obtain Abel's integral equation

$$\frac{\partial Q}{\partial x} = -2\int_{x}^{R} \frac{q(r)\,r\,dr}{\sqrt{l^2-r^2}}, \tag{6}$$

whose solution has the form

$$q(r) = -\frac{1}{\pi}\int_{x}^{R} \frac{\partial Q_q}{\partial x}\,\frac{dx}{\sqrt{x^2-r^2}}. \tag{7}$$

Usually q(r) is found by the numerical method. In that case the formulas for calculating the specific heat flow and the current density are

$$q(r_m) = -\frac{2}{\pi b}\sum_{i=m}^{n-1} Q_p C_{ki},\quad j(r_m) = -\frac{2}{\pi b}\sum_{i=m}^{n-1} J_p C_{ki}. \tag{8}$$

The error of the method of converting q(r) and j(r) by the relationships (8) for $m = 10$ is less than 1% for $r_m \le 0.9R$, and somewhat more than 1% for $0.9 < r_m < R$, where R is the radius of the arc spot.

It was demonstrated above that for finding q(r) and j(r) it is at first necessary to differentiate the experimentally obtained dependence Q(x, y) and J(x, y) with respect to the x coordinate or with respect to time. Differentiation can be carried out by quantization of the experimental curve manually by the graphic method or by a computer. The error in determining the derivative by such a method, even with computer calculation, may attain 20-25% or more [9]. When analog devices are used for differentiation, the error δ may be reduced to less than 1% [9]. Therefore, for the differentiation of electric signals from sensors, units of analog computers were used.

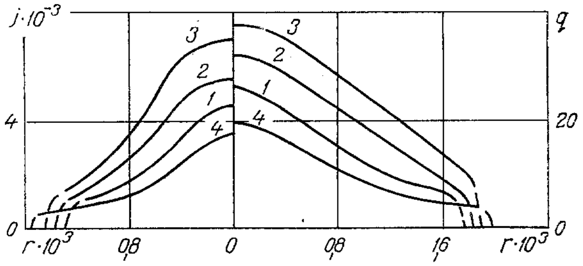

Fig. 3. Radial distribution of q (kW/cm^2) and j (A/cm^2) on the anode with $G_{Ar} = 0.2$ g/sec and currents: 1) 100 A; 2) 150; 3) 200; 4) $G_{Ar} = 0.1$ g/sec; J = 100 A, r, m.

Since the sectional electrode is shifted at low speed, we will take it that the shape of the spot is not distorted on account of the shifting, and that it is axisymmetric. We will, therefore, process the experimental curves by the generally accepted method for axisymmetric sources.

Among the thermophysical characteristics of a heat converter are: time constant, phase—frequency characteristic, sensitivity threshold, and limits of measurement. The time constant of the sectional electrode of a PSE, experimentally measured upon establishment of a regular thermal regime in the working space, was found to be equal to 0.8-1.1 sec in dependence on the speed of the cooling water. The maximally possible recorded frequency of the fluctuations of the heat flow is equal to 1.6 Hz, the sensitivity threshold is 1.5 W.

The resulting error of measurement of j(r) and q(r) can be evaluated by the formulas

$$\frac{\Delta J}{J} = \mu + \delta + \frac{\Delta J}{J} + \frac{\Delta R}{R}, \quad \frac{\Delta q}{q} = \mu + \delta + \frac{\Delta G}{G} + \frac{\Delta T}{T} + \frac{\Delta R}{R}.$$

To the obtained errors we must add methodological errors due to the numerical solution of Abel's integral equation (1%), heat losses from the surface of the sectional electrode due to convection and exchange by radiation (1%).

The total errors entailed by the newly devised method are as follows: $\Delta J/J \approx 7\%$, $\Delta q/q \sim 10\%$. In addition to that, errors may arise in measurements of the heat flow because of inaccurate assembly of the PSE. The sectional electrode has to be made with great care so that it fits closely against the nozzle shell. There must not be any gas leaks between the electrodes. The sectional electrode has to move freely over the surface of the flat electrode.

Measurements were carried out at currents of 100, 150, 200, 250 A and at flow rates of argon of 0.1, 0.2, 0.3, $0.45\cdot10^{-3}$ kg/sec. The limit of measurement according to current was given by the stability of the sectional electrode.

During the process of measurement the arc current and voltage were maintained constant with an accuracy of ±3%. In the transition of the arc from one section to another no current pulsation was noted. This indicates that in the investigated regimes, one diffuse spot forms on the surface of the anode.

The maximum values of the density of the heat flow to the anode of a HCP with reciprocal polarity (Fig. 3) were 5-10 times higher than for freely burning arcs and HCP with direct polarity [3-5]. However, even in these works some values of q with a current of 200 A have magnitudes 3 times larger than when calculated by the formula

$$q_\lambda = \lambda \frac{\Delta T}{\Delta x} \tag{9}$$

for a copper plate 3 mm thick with boundary conditions corresponding to the experiment. The authors did not offer any explanation of the observed phenomenon.

To obtain a qualitative explanation of the results of measuring q that considerably exceed the value of q_λ, we will examine the operation of a sectional electrode during the process of measurements. Via the heating spot, a heat flow reaches the surface of the electrode, and this heat flow spreads in all directions into the bulk of the electrode. When

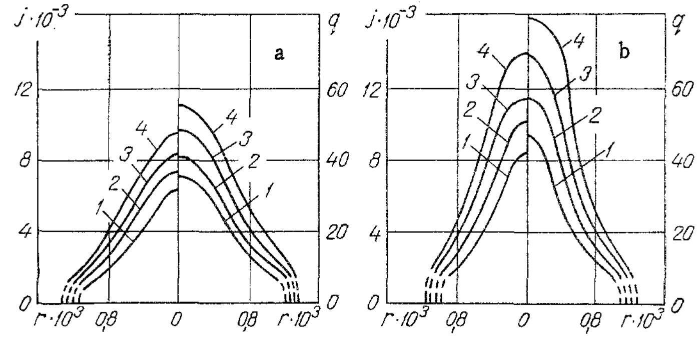

Fig. 4. Radial distribution of q and j on the anode with currents: 1) 100 A; 2) 150; 3) 200; 4) 250 A; a) $G_{Ar} = 0.3$ g/sec; b) $G_{Ar} = 0.45$ g/sec.

the heating spot has a small diameter (2–5 mm), the spread of the heat into the bulk of the electrode leads to an apparent increase in the size of the spot, and consequently to a lower "effective" density of the heat flow through the electrode. In consequence of the peculiarities of the design of sectional electrodes, which have a thermally and electrically insulating interlayer between the sections, spreading of the heat in each section occurs only from that part of the heating spot which crossed the section boundary. Thus, when the column of the arc is shifted across the boundary of a section, we measure the distribution of the heat flow acting on the surface of the electrode. Obviously, the possibilities of reducing the densities of the heat flow exceeding the values calculated by (9) without fusion of the surface of the electrode will be ever smaller with increasing surface of the heating spot.

Unlike the freely burning arc [3-5], where q and j do not have a distinct boundary, the radial distributions of q and j in our case (Fig. 4) do have a distinct boundary. The diameter of the anode spot is limited by the diameter of the outlet opening of the nozzle and by the flow rate of the stabilizing argon. When the flow rate of argon increases by a factor of 4.5, the diameter of the anode spot decreases by 38%. Simultaneously, the values of q and j at the center of the spot increase by a factor of almost 2.5. If we take it that the diameter of the anode spot is proportional to the flow rate of the stabilizing argon, then with a current $J = 100$ A and $G_{Ar} \to 0$, the diameter of the anode spot tends to the diameter of the nozzle channel of the plasmatron.

In all cases the thermal diameter of the anode spot is 8–25% larger than the electric diameter. This is due to the convective heat transfer from the hot plasma via the boundary layer and to the radiative heat transfer from the arc. For the same reasons the Volta equivalent in our experiments fluctuated within the limits 6.2–7.4 V, i.e., it was somewhat higher than in [10] where it was equal to 6 V.

It must be pointed out that if the flow rate of stabilizing argon is less than 0.10 g/sec with $J = 100$ A, or the current is increased to more than 200 A with $G_{Ar} = 0.2$ g/sec, the insulator of fabric glass laminate is destroyed and the operating regime of the plasmatron is upset. When the current was more than 250 A, with any flow rate of argon whatever, burns occurred on the boundary of the sectional electrode, and the operating regime of the PSE also changed.

NOTATION

T_q, temperature of the sensor; T_u, measured temperature; τ, time constant; v, speed of the sensor; x, coordinate; ΔS, surface area of the segment; Q_q, total heat flow to the sensor; n, number of zone into which the segment was divided in the direction of the OX axis; k, number of zones into which the segment was divided in the direction of the OY axis; R, radius of the heat or current spot; j, current density; q, heat flow density; $J_p = \partial J/\partial x$; $Q_p = \partial Q/\partial x$; b, subinterval of the experimental curve; c_{ki}, coefficients of [11]; λ, thermal conductivity; J, current to a section; δ, error of differentiation; μ, dynamic error of measurement of heat flows.

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THERMOPHYSICAL PROCESSES IN ELECTRIC CONTACTS UPON PASSAGE OF LET-THROUGH CURRENTS

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UDC 621.3.064

The article presents a theoretical calculation of the thermophysical processes in the region of constriction of the streamlines of electric contacts. The problem is solved by a numerical method.

The passage of an electric current is accompanied by the heating of the region of constriction of the electric contacts. At sufficiently high temperatures attained on the contact surface, the contacts become welded together, and this welding may occur in the solid phase as well as in the case of melting of the material of the contacts. When the currents are of sufficient intensity, there may, in addition to welding, also occur deflection of the movable contact under the effect of electrodynamic forces and forces of thermal origin. Since the phenomena of welding and deflection of contacts largely determine the operational reliability of contact systems of electrical apparatuses, the study of these phenomena is a very topical task. The present article theoretically describes the processes of heating and welding of contacts, and it also determines the conditions under which their deflection occurs.

A real conducting contact surface consists of a number of contact spots which are randomly distributed over the apparent contact surface. The higher the degree of dispersion of the contact microareas is, the lower is the heating of the contact surface and the higher are the currents at which welding and deflection of the contacts occur. From this point of view, the most unfavorable is single-point contact which was made the basis of the present examination. Following [1], we assume that the streamline passes from one contact to the

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V. I. Lenin Kharkov Polytechnic Institute. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 43, No. 1, pp. 110-117, July, 1982. Original article submitted April 10, 1981.

0022-0841/82/4301-0790$07.50