# MEASUREMENT OF THE RADIAL DISTRIBUTIONS OF THE THERMAL-POWER PARAMETERS AT THE ANODE OF A HIGH-CURRENT, LOW-PRESSURE, ARC DISCHARGE

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The radial distributions of the thermal-power parameters at the anode of a high-current, low-pressure, arc discharge with a hollow cathode are presented, and a function describing these distributions is proposed.

High-temperature technological processes employing plasma-arc energy sources, operating stably at pressures from $5 \cdot 10^{-3}$ up to 1.0 Pa, have in the past few years been increasingly adopted in industry. The most commonly used energy source of this class, in our opinion, is the arc discharge with a hollow cathode (ADHC), which is currently employed in commercial high-temperature technology, in particular, in welding processes [1].

Efficient realization of high-temperature technological processes requires a knowledge of the character of the thermal effect of the energy source in the treatment zone; it can be evaluated if thermal parameters such as the power $P_a$ liberated in the anode of the ADHC, the radial distribution of the specific heat flux q(r), as well as the degree of its concentration, are known [2]. The numerical values of these parameters, especially q(r) as a function of the parameters of the regime of ADHC at currents exceeding 100 A, however, are not known. The lack of these data as well as the fact that the radial redistribution of the current density j(r) on the anode of the ADHC is unknown also make it difficult to construct a theory of anode processes [3].

This work is devoted to the measurement of the above-indicated thermal-power characteristics at the anode of ADHC in a vacuum as well as to the determination of their dependence on the parameters determining the discharge regime.

In the experiments performed the determining parameters of the ADHC regime were varied within the following limits: discharge current I = 100-350 A, length of the arc gap L = 0.8-2.5 cm, injection of the plasma-forming gas (argon) through the cathode cavity Q = $(0.7\text{-}1.5) \cdot 10^{-3}$ g/sec, diameter of the cathode cavity d = 0.3-0.4 cm, and the working pressure in the chamber p = $(5\text{-}6) \cdot 10^{-2}$ Pa.

The power $P_a$ liberated at the anode, the specific heat flux q, and the current density j are best determined experimentally, in our opinion, with the help of the well-known sectioned-anode method [4]. Unfortunately, this device [4] does not permit measuring the thermal parameters for highly concentrated energy sources, such as ADHC [1]. The use of a rotating sectioned anode [5] significantly extends the upper limits of the measurement of $P_a$, q, and j, and with its help it is in principle possible to determine the thermal-power parameters of ADHC. Our calculations show, however, that the accuracy with which these characteristics, especially q(r), are measured with the help of a rotating sectioned anode is low, primarily because of the presence of sliding electric contacts in the measurement circuits, which introduce significant errors in the measurements. In addition, the use of this device in a vacuum chamber complicates its operation, because of the low reliability of the rotating seals, intended for airtight injection of cooling water.

In this case, the foregoing thermal-power parameters of ADHC were measured on a moving sectioned anode, which was put into reciprocal motion with the help of a crank gear.

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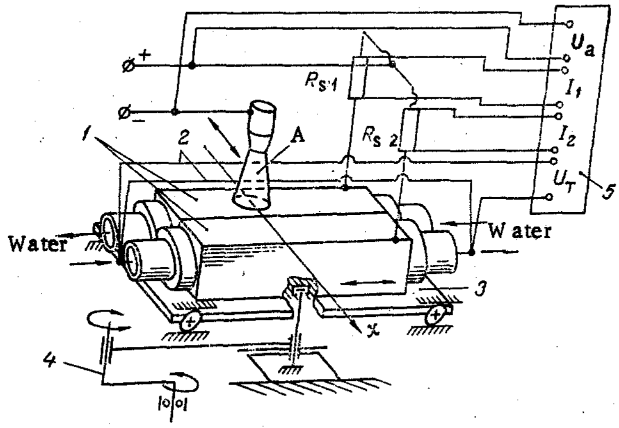


Fig. 1. Apparatus for measuring the specific heat flux and current density: 1) sectioned, water-cooled anode; 2) differential thermocouple; 3) trolley; 4) crank gear; 5) loop oscillograph; A, arc discharge; $R_{S1}$, $R_{S2}$, shunts for measuring the discharge current; $I_1$, $I_2$, discharge currents in the anode sections; $U_T$, potential difference on the differential thermocouple; $U_a$, arc voltage.

The apparatus (Fig. 1) has stationary electric contacts both in the discharge current circuit and in the measuring circuit; this enables more accurate measurements.

To evaluate the technical possibilities of the apparatus, the following characteristics were determined: the time constant of the sensor $\tau$, the average linear velocity $V_c$, and the frequency of the reciprocal motion $f_c$, as well as the thresholds of sensitivity and the upper limits of the measurements of the parameters q and j.

The quantity $\tau$ was determined by the procedure described in [6]. For our case $\tau$ = 16.3 sec. To avoid destruction (melting of the surface heated by the arc) of the copper anode sections, the frequency of the reciprocal motion of the sensor must not be less than 2 Hz, and the average velocity of the anode surface relative to the discharge must exceed 1.3 cm/sec. As the investigations showed, the structure of the ADHC in the region near the anode and its external electrical characteristics for velocities $V_c$ ranging from 0 to 4 cm/sec remained virtually unchanged.

The sensitivity threshold of the sensor in determining q equaled 200 W/cm$^2$; for j it equaled 20 A/cm$^2$. The upper limit for measuring q, at which the anode sections were not damaged, reached values of the order of $(6.0\text{–}7.0)\cdot 10^4$ W/cm$^2$.

The experimental procedure employed made it possible to measure the distribution of the integral values of the heat flux P(x) and current I(x) of the ADHC along the x axis (Fig. 1). The transformation to the distributions q(r) and j(r) sought was then performed with the help of the Abel inversion [7]:

$$f(r) = \frac{1}{\pi}\int_r^R \frac{F''(x)\,dx}{\sqrt{x^2 - r^2}}. \tag{1}$$

The integral equation (1) is an improperly posed problem in mathematical physics, and the accuracy with which q(r) and j(r) are determined depends strongly on the error introduced in processing the experimental data [8].

In this work Eq. (1) was solved with the help of the Abel inversion algorithm based on cubic smoothing splines [8], which give quite high computational accuracy [9]. In so doing, Eq. (1) is represented in the form

$$f(r) = -\frac{1}{\pi}\left(-\frac{S(r)}{\sqrt{R^2 - r^2}} + \sum_{\substack{i=m\\ r=x_m}}^{N-1}\int_{x_i}^{x_{i+1}} \frac{x\,(S(x) - S(r))}{\sqrt{(x^2 - r^2)^3}}\,dx\right). \tag{2}$$

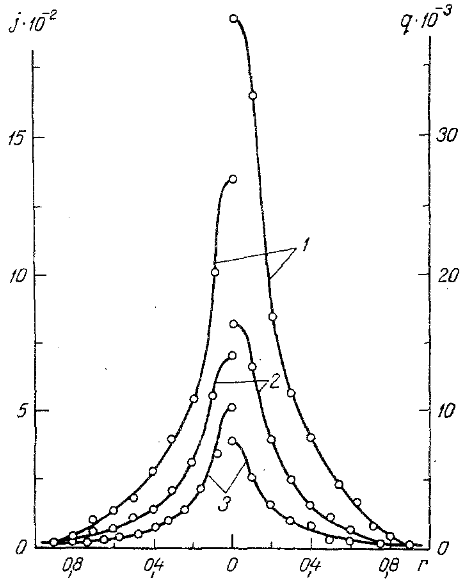


Fig. 2. Radial distributions of the specific heat flux and current density at the anode of ADHC; d = 0.3 cm, L = 1.6 cm, Q = $1 \cdot 10^{-3}$ g/sec for the discharge currents I = 350 A (1), 200 (2), and 100 (3). j, A/cm$^2$; q, W/cm$^2$; r, cm.

The cubic smoothing spline S(x) employed in the solution of Eq. (2) passes in a definite neighborhood, fixed by the smoothing parameter $\alpha$, from the measured values. Finding the parameter $\alpha$ presented significant difficulties, since the covariation matrix of the measurement noise was not determined. To find the parameter $\alpha$ we employed the method of "minimization of the discrepancy vector" [8], which can be realized quite efficiently on a computer [9].

In [10] it was pointed out that the experimental curves q(r) and j(r) reflect the real distributions with distortions and include a random error. Analysis of the measurement process and the processing of the experimental results showed that the most significant errors are the dynamic, instrumental, and methodical errors.

The dynamic measurement errors are determined by the continuous displacement of the ADHC relative to the interface of the sections, the reciprocal motion of the sensor itself, and also by the finite flow velocity of the cooling water. Estimation of the dynamic error by the method described in [6] showed that it does not exceed $\varepsilon_d = 4\%$.

The instrumental error, determined by the accuracy of the measuring devices employed, equals $\varepsilon_{iq} = 1.9\%$ for q and $\varepsilon_{ij} = 1.4\%$ for j.

The error of the mathematical analysis method employed, determining the magnitude of the methodical error and evaluated with the help of a test problem, equaled $\varepsilon_{mj} = 3\text{-}6\%$ for the distribution j and $\varepsilon_{mq} = 4\text{-}8\%$ for q [9].

As an example, Fig. 2 shows typical radial distributions q(r) and j(r) at the anode of a low-pressure ADHC.

The characteristic feature of the distributions q(r) and j(r) is that in the central part of the heating spot the parameters q and j vary rapidly and at a distance of approximately 0.5 of the spot radius their values equal 10-15% of the maximum values at the center of the spot. It should also be noted that in all cases the diameter of the heating spot practically equals the diameter of the anode spot.

The approximation of the functions q(r) and j(r) with the help of the well-known normal (Gaussian) distribution law, as was done, for example, in [7, 10], does not reflect the real character of the indicated distributions.

With the help of a computational experiment we were able to find the analytical function describing quite accurately the distributions q(r) and j(r) at the ADHC anode. It is convenient to express this function as a sum of two Gaussian curves:

$$f(r) = f_{2m}\left(A\exp\left(-k_s r^2\right) + B\exp\left(-k_0 r^2\right)\right), \tag{3}$$

where A and B are coefficients, with whose help the quantity $f_{2m}$ in each of the Gaussian curves is determined, and A + B = 1; $k_s$ and $k_0$ are the so-called "coefficients of concentration" of the Gaussian curves.

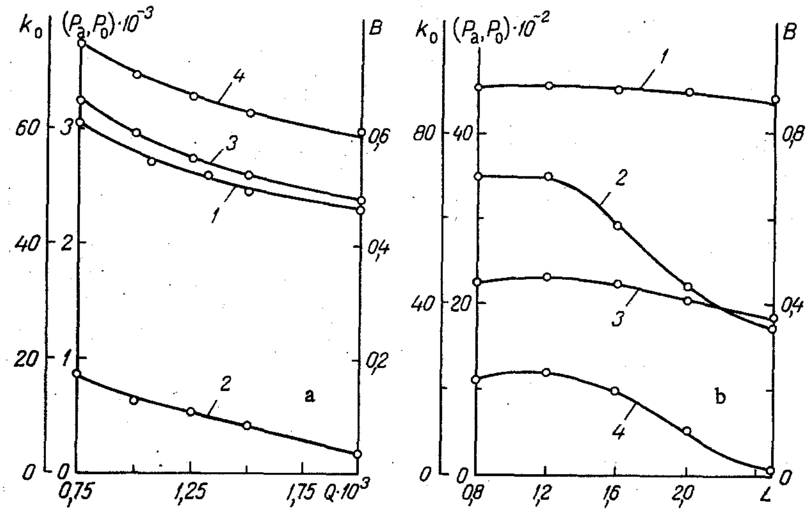


Fig. 3. Thermal-power parameters of ADHC versus the argon flow rate (a) (d = 0.3 cm, L = 1.2 cm, I = 150 A) and versus the width of the arc gap (b) (d = 0.3 cm, I = 210 A, Q = $1 \cdot 10^{-3}$ g/sec): $P_a$ (1), $P_o$ (2), $k_o$ (3), B (4). $k_o$, $cm^{-2}$; ($P_a$, $P_o$), W; Q, g/sec; L, cm.

In so doing one of the Gaussian curves

$$f_0(r) = B f_{2m} \exp(-k_0 r^2) \tag{4}$$

approximates most accurately the obtained distributions in the central part of the heating spot of ADHC, while the other

$$f_s(r) = A f_{2m} \exp(-k_s r^2) \tag{5}$$

describes the function f(r) at the periphery of the heating spot. It is interesting that in the region of the ADHC regimes studied the coefficient of concentration $k_0$, as a rule, exceeded $k_s$ by at least an order of magnitude. In addition, $k_s$ remained virtually constant and equaled $k_s$ = 4-6 $cm^{-2}$, while the coefficient of concentration $k_o$ varied over a wide range $k_o$ = (40-65) $cm^{-2}$. The maximum values of $k_o$ corresponded to the current range 100-150 A. It was also established that as the discharge current increases from 100 to 350 A the effective heat power $P_a$ and its relative fraction $P_o$, liberated predominately in the central part of the heating spot, equal to approximately (1.5-2.0)d, increase appreciably:

$$P_0 = 2\pi q_{2m} B \int_0^R \exp(-k_0 r^2)\, r dr. \tag{6}$$

Thus, for example, $P_a$ increases from 1.5-2.0 to 10-11 kW, while $P_0$ changes from 5 to 20% relative to $P_a$. In addition, the maximum specific heat flux reaches values of 50-60 $kW/cm^2$, which is almost an order of magnitude greater than the values of $q_{2m}$ for high-pressure arcs burning in an argon atmosphere [4, 5].

Thus, according to the classification of energy sources based on their effect on the worked material [11], the ADHC in the studied range of parameters can be referred based on its thermal characteristics to the class of highly concentrated sources, since for it the maximum specific heat flux reaches values of $q_c^{(2)}$ (the critical flux density for which the surface of a semiinfinite body is heated up to the boiling point).

Increasing the injection of plasma-forming argon through the cathode cavity uniquely increases the diameter of the heating spot, as well as reduces the parameters $k_o$, $P_a$, and $P_o$ (Fig. 3a). For example, for the cathode cavity diameter d = 0.3 cm argon injection of the order of Q = $(1.7-0.9) \cdot 10^{-3}$ g/sec is optimal from the viewpoint of stable burning of ADHC and obtaining an energy source with maximum action.

The effect of the length of the arc gap, with the other parameters of ADHC remaining constant, on the radial distributions q(r) and j(r) is not unique (Fig. 3b). Thus as the length of the arc gap increases from 0.8 to 2.5 cm the current density at the center of the heating spot decreases, while the power liberated at the anode remains practically unchanged. In addition, the values of $k_0$, $P_0$, and $q_{2m}$ for the ADHC are maximum with an arc gap length of the order of 1.2-1.6 cm. Thus, in this range of arc lengths the ADHC has the maximum thermal effect on the material, and this feature of the discharge must be taken into account in high-temperature technological processes, in particular, welding.

## NOTATION

$P_a$, effective thermal power, W; $P_0$, relative thermal power liberated in the central part of the heating spot, W; R, radius of the heating spot, cm; q, specific heat flux, W/cm²; $q_{2m}$, maximum value of the specific heat flux, W/cm²; j, current density, A/cm²; I, discharge current, A; L, length of the arc gap, cm; Q, rate of injection of the plasma-forming gas, g/sec; d, diameter of the cathode cavity, cm; τ, time constant, sec; $V_c$, linear velocity, cm/sec; $f_c$, frequency of reciprocal motion, Hz; x, r, instantaneous coordinates, cm; F(x), generalized experimental function; f(r), generalized distribution function; S(x) and S(r), cubic smoothing splines; $f_{2m}$, maximum value of the function f(r); α, smoothing parameter; $k_0$ and $k_s$, coefficients of concentration, $cm^{-2}$; $q_c^{(2)}$, critical specific heat flux density, W/cm²; $\varepsilon_d$, dynamic error; $\varepsilon_{iq}$ and $\varepsilon_{ij}$, instrumental errors in the measurements of q and j, respectively; and, $\varepsilon_{mq}$ and $\varepsilon_{mj}$, methodical errors in the measurements of q and j, respectively.

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