THERMAL ACTION OF AN ELECTRIC ARC ON THE WALL OF A PLANAR GAP

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The distribution of thermal flux from a dc arc with i = 200-400 A located in a moving planar gap is studied experimentally. A model is proposed for the interaction of the moving heated gas flow, the dielectric wall, and the calorimeter.

Electric arc heaters have found widespread use in the study of matter at high temperature and in a number of highly efficient processes for producing protective and decorative coatings [1, 2]. Effective use of the supplied energy in heating material is achieved in plasma devices in which the current-conducting arc channel is located in a gap formed by walls of solid materials. A model and structure of the plasma formation thus obtained was studied in [3, 4]. Calculation of the thermal flux in the gap wall from an impulsive arc with maximum current $i_m > 1$ kA moving at high velocity was carried out in [5] with the assumption of an arc shape of rectangular section, transmission of all energy liberated in the arc to the walls, and absence of wall ablation.

Wall heating in the presence of phase transitions and ablation is of significant interest both theoretically and for practical applications. The multiplicity and little-studied nature of physicochemical processes in the zone of contact between the arc and the affected wall complicates use of theoretical methods for determining thermal flux values and has stimulated refinement of experimental techniques.

Calorimetric sensors are used to measure the thermal flux to the gap wall. The results of [6] indicate the promise of thin film thermocouple sensors for this purpose. In order to investigate the possibilities of an arc with i = 200-400 A with regard to heating of solid materials the time dependence of thermal flux to a film thermocouple installed in a dielectric (silicate material: $\sim$90% SiO_2) wall of a moving gap was studied.

The intensity of wall ablation was controlled by changing the rate of wall displacement relative to the nonmoving lengthy arc (ℓ_a = 150 mm) generated by a PS-1V plasmotron (Fig. 1) [7]. The plasmotron working gas was nitrogen, with distance between gap walls ℓ = 6 mm, and gap displacement rates of v = 0.1-0.4 m/sec. After arc action on the surfaces, a fused layer 0.03-0.3 mm thick was found. Transition to an ablation-free wall heating regime was determined from the absence of a fused layer, and for the given current range was achieved at v = 0.2-0.3 m/sec.

The silicate material used for the gap walls manifested three temperature intervals of intense gas liberation: 200-300, 1000-1200, and 2200-2300°C [8]. Therefore, the quantity and composition of impurities in the gas layer adjacent to the wall will be determined by the temperature range in which the wall temperature lies. In the velocity range 0.08-0.15 m/sec the wall temperature lay in the range 1500-2200°C and Na, K, SiO_2 vapors were present in the layer of gas at the wall [8].

At a velocity of 0.08 m/sec and L = 0.025 m after spark action the surface showed a porous structure with through-pores and weak adhesion of the fused layer to the base material, i.e., in this case evaporation of chemically bound water from the base material occurs, and not only the surface layer, but also deep layers of the material participate in the ablation process. With increase in velocity v the thermal effect decreases, which leads to a decrease in the quantity of through-pores and content of Na, K, SiO_2, and H_2O vapor in the boundary layer.

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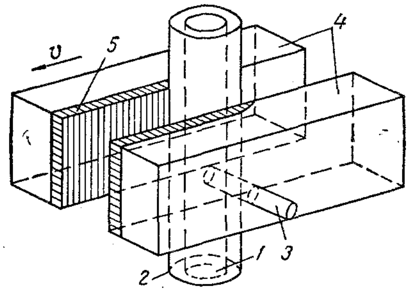

Fig. 1. Schematic diagram of arc with gap: 1) central core of arc; 2) peripheral zone; 3) calorimeter; 4) dielectric specimens; 5) fused layer.

At a distance from the cathode L = 0.076 m the arc has a large diameter, and deforms upon entry to the gap, as a result of which its cross section takes on the form of an ellipse, with the high temperature zone retaining cylindrical symmetry. Therefore, during gap motion the material surface is heated by low-temperature zones of the plasma column, which produces evaporation of volatile fractions even before arrival of the higher temperature arc zone. In such regimes the surface shows a smooth fused layer of material with no visible traces of boiling of the melt.

Analysis of photographs of the plasma column taken with an SKS-1M camera (during the measurement process) revealed that the arc has a central core and a peripheral zone near the wall, separated by a sharply defined boundary. Visible turbulent perturbations were absent in the arc core and at its periphery, indicating the laminar character of the plasma flow. Moreover the plasma column shows practically no change with time, and its core has no significant transverse gradients. On the basis of these facts, to determine the thermal flux q(r) as a function of distance from the plane of symmetry of the arc, perpendicular to the wall, it is sufficient to make measurements in 10 zones, which for a plasma column diameter of ∿ 10 mm is achieved at d = 1 mm. This conclusion was later confirmed by analysis of spatial spectra of the q(r) distribution. It developed that the spectra were limited by wave number values of 0.07 mm^{-1}. At the same time, according to the estimates of [9], a sensor d = 1 mm in diameter is capable of registering a significantly larger interval of spatial frequencies with wave numbers up to 0.4 mm^{-1}. Therefore, the 1-mm-diameter calorimeter used in the present study provided sufficient spatial resolution of q(r). Use of a smaller diameter calorimeter would be complicated by the need to consider lateral heating and transverse inhomogeneity of the temperature field in the calorimeter bar [10].

Data processing was performed on a CM-3 computer using programs allowing data input both directly from the equipment or from another device in the case of automatic generation of initial data. The data were first stored in permanent system memory, whereupon at any desired time service programs were used to examine them in convenient (tabular or graphic) form on the display screen and evaluate them with consideration of the problem in question.

The processing programs allowed generation of values of thermal flux to the calorimeter wall as a function of position of the plasma column q(r) and size of the interaction zone δ and determination of energy supplied to the surface W and thermal action time t_a. To do this the following algorithms were used:

$$q(k\Delta t) = \sqrt{\frac{\rho c\lambda}{\pi\Delta t}} \sum_{s=1}^{k} (T_s - T_{s-1}) \frac{2}{\sqrt{k-s+1}+\sqrt{k-s}}, \quad (1)$$

$$\delta = vn\Delta t, \quad (2)$$

$$W = \sum_{k=1}^{n} q(r_k)\,\Delta r, \quad (3)$$

$$t_a = n\Delta t, \quad (4)$$

where n is chosen from the condition

$$\frac{\sum_{k=1}^{n} q(r_k)\,\Delta r}{\sum_{k=1}^{n+1} q(r_k)\,\Delta r} \geqslant 0{,}99. \quad (5)$$

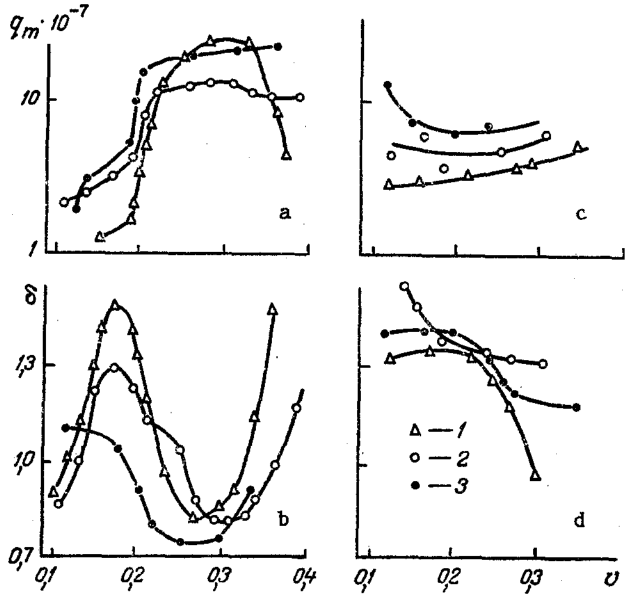

Fig. 2. Maximum thermal flux $q_m(v)$ and action zone size $\delta(v)$ vs velocity of gap motion: a, b) L = 25 mm; c, d) L = 16 mm; 1) 200 A; 2) 300; 3) 400. q_m, W/m²; δ, cm; v, m/sec.

Equation (1) was obtained by solution of the one-dimensional converse thermal conductivity program with boundary condition of the second sort for a semiinfinite bar with the assumption $T_0 = 0$.

Using the algorithms presented, 60 experiments were analyzed involving heating of the gap wall by an arc with i = 200, 300, 400 A at distances from the cathode L = 0.025 and 0.076 m and gap motion velocities v = 0.1-0.4 m/sec. It was found that with increase in current the maximum thermal flux q_m and size of the action zone increase significantly. The functions $q_m(v)$ and $\delta(v)$ are shown in Fig. 2. At L = 0.025 m the maximum thermal flux in the velocity range 0.1-0.3 m/sec increases with increase in gap velocity. The size of the interaction zone changes nonmonotonically. At L = 76 mm the maximum thermal flux depends only weakly on velocity, while the width of the interaction zone falls with increase in velocity.

The information presented on the character of the thermal effect of an arc refers to the surface of a metallic bar installed in the dielectric wall of the gap and having geometric dimensions and thermal conductivity the same as the calorimeter. These results are of independent interest for optimization of high temperature surface processing of metallic parts of limited size. At the same time, for some problems it is necessary to know the parameters of the dielectric gap wall thermal regime for arc heating. In this case the values of q_m, δ, W, t_a obtained cannot be used to describe the process on a dielectric surface. This was demonstrated by comparing the power delivered to the gap wall

$$W = 2l_a \int_0^r q(r)\, dr$$

calculated with the results of q(r) measurements by a metallic calorimeter to the power $W_e = Ui$ expended in the arc. It proved to be the case that for the entire current range studied $W/W_e = 4\text{-}5$. In our opinion, this is related to the two following facts. First, the temperature of the probe is markedly less than the wall temperature. In fact, in [11], wherein spectral methods were used to study arc heating of gap walls of a silicate material, it was established that at i = 450-540 A and v = 0.11 m/sec and d = 6 mm, i.e., conditions close to those of the present experiment, the surface temperature was 2300°K. At the same time, the data of the film thermocouple indicate that the temperature of the metal sensor does not exceed 1000°K. Second, the gas near the arc is moving at a quite high velocity (∿ 100 m/sec). As a result of the action of these factors an additional thermal flux appears, caused by flow of hot (at the wall temperature) gas onto the cold sensor.

The value of the thermal flux to the sensor can be estimated by considering the gas motion at the wall as a steady-state flow (with heat liberation) in a semiinfinite space, bounded by a plane with a fixed temperature distribution. The assumption that the region occupied by the flow is semiinfinite is justified by the fact that the transverse dimension of the plasma formation is such greater than the sensor diameter, while the steady-state assumption is justified by the quite low transverse velocity of the plasma. We will assume that the temperature of the plane is equal everywhere to the constant value T_W, except on the sensor surface, which has a temperature T_S. It will be convenient to represent the temperature in the gas as the sum of the unperturbed value T_0, realized in the absence of the sensor (i.e., at $T_W = T_S$), and a perturbation δT caused by the presence of the sensor. Accordingly, the thermal flux into the sensor is the sum of the flux to the wall q_W in the absence of the sensor and the flux δq caused by the difference of sensor and wall temperatures. It can easily be seen that δT is determinable from an equation describing heat propagation into a semiinfinite moving medium without heat sources with initial zero temperature from a plate of finite dimensions located on the boundary at fixed temperature $T_W - T_S$.

Considering the linear dependence of gas velocity on distance from the wall in a laminar boundary layer, we evaluate the characteristic scale h of the temperature drop δT for the case of sufficiently high gas velocities from the condition of equality of the gas transit time past the sensor $\tau_t \simeq d|\nabla u|h$ and the characteristic heat propagation time $\tau = h^2/a$, where $|\nabla u|$ is the velocity gradient at the wall. Considering that at low gas velocities $h \sim d$, we write the additional thermal flux to the sensor in the form

$$\delta q \sim \lambda_g (T_W - T_S) h^{-1} \sim \max \begin{cases} \lambda_g (T_W - T_S)\, d^{-1}, \\ \lambda_g (T_W - T_S)\, (da)^{-\frac{1}{3}} (\nabla u)^{\frac{1}{3}}. \end{cases} \quad (6)$$

It follows from Eq. (6) that the additional flux to the sensor depends on the temperature difference between sensor and wall, the sensor size, and the velocity gradient and thermophysical characteristics of the gas.

In the experiments under consideration $T_W = 2300°K$, $T_S = 950°K$, $d = 1$ mm. At a boundary layer thickness $\Delta x = 0.5$ mm, velocity $u = 100\ m \cdot sec^{-1}$, temperature $T_g = 5000°K$ outside the boundary layer we find $\nabla u = 4 \cdot 10^5\ sec^{-1}$ and temperature gradient $\nabla T = 5.4 \cdot 10^6\ °K \cdot m^{-1}$, defining the thermal flux into the wall far from the sensor. Taking $a = 10^{-4}\ m^2 \cdot sec^{-1}$, we find the ratio of the thermal flux into the sensor and the wall:

$$\frac{q_S}{q_W} = \frac{q_W + \delta_q}{q_W} \sim (T_W - T_S)\,(da)^{-\frac{1}{3}} \cdot (\nabla T)^{-1} (\nabla u)^{\frac{1}{3}} \simeq 4. \quad (7)$$

It is evident from the above evaluation that the thermal flux into a sensor the temperature of which is markedly less than the wall temperature may be in qualitative agreement with experimental data comparing the energy supplied to the arc to the thermal flux recorded by the metallic sensor.

As follows from Eq. (7), if the tmperatures of the surfaces are equal, the thermal fluxes into wall and sensor should coincide. This is confirmed by W_e/W calculations from measurements of q(r) by a copper calorimeter installed in a steel wall [6]. For this case, because of the similarity of thermophysical properties of wall and sensor, their temperatures may be considered equal to each other. For an arc with i = 30-75 A a value of $W_e/W = 1$-1.3 was found, indicating approximate equality of the powers supplied to the arc and recorded by the sensor.

It follows from the above that to determine the thermal flux from the arc to the gap wall it is necessary to know the temperatures of sensor and wall surfaces, as well as the boundary layer parameters. Since obtaining a reliable set of such data is usually difficult, the experimenter should use a sensor of material with thermophysical properties similar to those of the wall material and surface temperature not far removed from the wall temperature.

It should be stressed that the presence of phase transition on the wall will not allow achievement of equality between sensor and wall temperatures at every moment of time. From estimates based on Eq. (6) it follows that in the present experiments the temperature difference between wall and sensor tolerable to attain 50% accuracy in measuring thermal flux into the wall should not exceed $\sim 250°$.

The results obtained permit evaluating the maximum thermal flux from an arc with current of several hundred amperes. Use of gap walls of silicate material can lead to fluxes up to $4 \cdot 10^8$ W/m^2 to limited area metal surfaces with good thermal conductivity. Obtaining higher fluxes apparently will require use of gaps of more temperature-stable material. The maximum flux producable into a wall of silicate material comprises $\sim 1 \cdot 10^8$ W/m^2. The results presented may be used to optimize surface thermoprocessing of various materials. The method developed for determining the profile of the thermal flux from arc to wall and the programs for processing of the experimental data can be used to study nonsteady-state thermal fields in various high-temperature apparatus.

NOTATION

U, i, voltage, current; ℓ_a, arc length; ℓ, distance between gap walls; L, distance from cathode; q, q_m, q_w, q_s, thermal flux, maximum thermal flux, thermal flux into wall and sensor; r, distance; ρ, c, λ, density, specific heat, thermal conductivity; T_w, T_s, temperatures of wall and sensor surface; v, velocity; δ, width of action zone; W, energy supplied to surface; W_e, energy supplied to arc; t_a, action time; n, time step number; Δt, time interval; τ_t, τ, gas transit time past sensor and thermal conductivity time; h, characteristic scale of temperature drop; a, thermal diffusivity; λ_g, thermal conductivity of gas; ∇u, u, velocity gradient and gas velocity at wall.

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DISTURBANCE OF LOCAL THERMAL EQUILIBRIUM IN AN ELECTRIC-ARC ARGON PLASMA

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It is shown that allowance for the condition $T_e \neq T_h$ in determining the composition and transport properties and allowance for reabsorption of radiation permit refinement of the region of disturbance of local thermal equilibrium in electric arcs.

In calculating the characteristics of electric-arc devices, the choice of the arc model is very important. In a wide range of the parameters (current, gas flow rate, channel size) good agreement with the experimental characteristics can be obtained using an equilibrium model of an arc. At the same time, there are rather inconsistant data on the disturbance of local thermal equilibrium (LTE) in an electric-arc plasma. The disturbance of LTE in an

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