appropriate reaction product by the surface layer.

NOTATION

A, degree of transformation; b — β/α; c, concentration; D, diffusion coefficient; f, surface concentration; k_1, k_2, adsorption and desorption rate constants in the solid phase; l, linear dimension of the area occupied by one molecule; K, L, M, dimensionless parameters defined in (6); R, R_0, reaction front and particle radii, respectively; r, radial coordinate; S, fraction of surface layer filling; t, time; t_*, transformation time; α, adsorption rate constant from the gas phase; β, desorption rate constant in the gas phase; $\varkappa$ — $l'^2/\nu l^2$; ν, stoichiometric coefficient; ξ — R/R_0; τ — αt; τ_0, dimensionless duration of the induction period; φ, reagent concentration in the initial solid phase; the prime denotes quantities referring to the gaseous reaction product.

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HEAT EXCHANGE BETWEEN A LAMINAR AND PULSATING PLASMA JET AND A BARRIER

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The influence of the parameters of the plasma stream and their time variation on the intensity of heat exchange near the stagnation point of a blunt body is analyzed.

Technological processes based on the use of a low-temperature plasma are presently used in various branches of science and engineering. High-temperature gas streams are obtained by electric-arc heating of gas in plasmatrons. Since the main technological zone in the majority of plasma processes is the plasma jet generated by the heater, for its efficient practical use it is important to know the amount of the heat flux from the jet to the solid, which depends on the operating parameters of the plasmatron and the distance from the nozzle exit cross section to the barrier.

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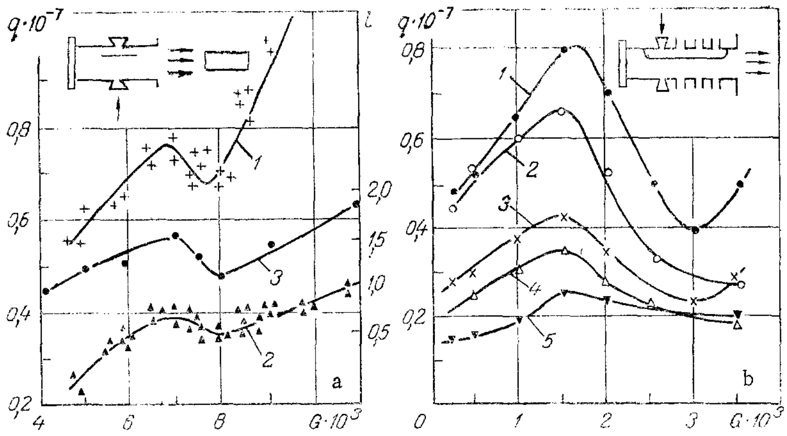

Fig. 1. Heat flux from a plasma jet to a barrier (W/m^2) at different gas flow rates (kg/sec) and distances from the nozzle cut: a) air, N = 120 kW, d = $2\cdot10^{-2}$ m; 1) x = $8\cdot10^{-2}$ m; 2) $13\cdot10^{-2}$; 3) relative length of luminous part of jet, l = 1 at G = $4\cdot10^{-3}$ kg/sec; b) argon, I = 70 A, d = $6\cdot10^{-3}$ m; 1) x = 10^{-2} m; 2) $1.25\cdot10^{-2}$; 3) $1.5\cdot10^{-2}$; 4) $1.75\cdot10^{-2}$; 5) $2\cdot10^{-2}$.

The heat fluxes to a solid from a plasma jet generated by an electric-arc gas heater of linear design with vortex stabilization of the discharge were measured experimentally. The gas outflow from the plasmatron nozzle was subsonic. The tests were conducted in the jets of plasmatrons with the following electrode sizes: nozzle diameter d = $(6\text{–}25)\cdot10^{-3}$ m, electrode length 0.1–0.24 m. Air, nitrogen, and argon were used as the plasma-forming media. Under steady conditions the specific heat flux was determined by the exponential method [1]. To measure the variable heat fluxes we used a probe and analog device developed at the Institute of Thermomechanics, Czechoslovakian Academy of Sciences (CSAS) [2].

The experimental results on the measurement of heat fluxes in the cores of jets generated by electric-arc heaters of air and nitrogen in the power range of 40–300 kW and the range of gas flow rates G = $(2.5\text{–}13)\cdot10^{-3}$ kg/sec can be described by the generalized dependence

$$q_0 = 10^3 d^{0.22} (G/d)^{0.98} (J^2/Gd)^{0.4} R^{-0.5}. \qquad (1)$$

The maximum measured heat fluxes reached $7\cdot10^7$ W/m^2.

Equation (1) allows one to calculate the heat flux to a barrier near the axis of the nozzle of the plasmatron. The heat fluxes decrease with greater distance from the nozzle cut. Measurements of the heat flux along the jet axis made for linear plasmatrons in the above-indicated ranges of gas flow rate, electric arc power, and diameter showed that the character of the decrease in q with an increase in distance is practically the same for the majority of regimes in the investigated ranges of the parameters. The heat-flux distribution along the axis in the case of the usual relatively short, laminar initial section of the jet can be described as

$$q_x/q_0 = \exp[-0.126\,(x/d)^{1.5}]. \qquad (2)$$

The established dependence is confirmed by test data obtained on linear plasmatrons with discharge chambers of different construction [2, 3].

As the experiment showed, with an increase in the gas flow rate one does not observe a continuous lengthening of the high-temperature luminous part of the generated jet. For each regime of heater operation there is some shortening of the jet at a certain gas flow rate, after which the jet again lengthens with a further increase in the flow rate. The intensity of heat exchange between the jet and the barrier varies correspondingly (Fig. 1). These facts can be explained by the character of the interaction of the plasma jet with the surrounding medium due to the development of intense turbulent pulsations in a given zone of the jet. The transition from the laminar to the turbulent regime of flow in the high-temperature air stream was observed in the range of $640 \leqslant \mathrm{Re} \leqslant 760$. The Reynolds number was determined from the gas parameters at the nozzle cut of the heater. The data presented for air confirm the results of measurements in an argon plasma jet (Fig. 1b) on the installation of the Institute of Thermomechanics, CSAS, with a sectioned anode.

The most characteristic electrophysical processes in the working chamber of an electric-arc gas heater is large- and small-scale shunting, which causes pulsations of the arc voltage and current. For plasmatrons with a self-established length and gas-vortex stabilization of the arc the amplitude of the voltage and current oscillations reaches several tens of percent of the mean value. Two groups of pulsations are distinguished by frequency [4]: low-frequency pulsations with a frequency of up to 2 kHz and high-frequency pulsations with a frequency of up to 100 kHz. The low-frequency pulsations have an amplitude about an order of magnitude greater than the amplitude of the high-frequency oscillations. Such behavior of the arc in the plasmatron channel results in pulsations of the parameters of the generated stream. Whereas in aerodynamic research, for example, pulsations of the parameters of the stream of heated gas are often undesirable, in plasma chemistry their role may be positive.

A small number of papers have been devoted to the study of the influence of pulsations of the parameters of the plasma stream on heat exchange at the stagnation point of a blunt body [5, 6], and the results presented in them do not give a clear answer to this question. The results of a theoretical calculation of heat exchange in the vicinity of the stagnation point of a body over which a laminar stream of dissociated gas flows are presented in [7] in the form

$$q = 0.76R^{-0.5}\,\mathrm{Pr}^{0.6}\,(\rho\mu)_w^{0.1}\,(\rho\mu)_s^{0.4}\left[1+(\mathrm{Le}^{0.52}-1)\frac{h_D}{h_0}\right](h_s-h_w)\left(2\,\frac{p_s-p_\infty}{\rho_s}\right)^{0.25}. \quad (3)$$

A comparison of the results of a calculation of heat exchange based on the theory of Fay and Riddell with the experimental data of [5, 6] showed that in the first case the test points lie considerably above the calculated ones while in the second case they practically coincide.

Under these conditions of the interaction of a solid with a plasma stream generated by an electric-arc gas heater the direct radiation of the arc can fall on the specimen. However, the influence of the radiant component on the heat exchange is neglected in such calculations. The admissibility of this in view of the small characteristic size of the test modes was pointed out in [8]. Moreover, the results of [9] showed that at the levels of stream enthalpy occurring at suborbital and orbital flight velocities of aircraft the radiant heat flux is negligibly small compared with the convective flux. Our estimate based on data presented in [10] showed that the radiant component did not exceed 5% near the nozzle cut and decreased sharply with greater distance from the exit nozzle.

We made a theoretical and experimental investigation of the influence of pulsations of the parameters of the plasma jet on heat exchange with a barrier. We considered a model process consisting of the periodic stepwise variation of the stream temperature between certain arbitrary values with flow over a spherical barrier with a constant temperature. The properties of the gas were taken as constant and subsonic laminar flow was considered.

The dependence describing the results of the numerical calculations for the case of a single stepwise change in the stream temperature has the form [11]

$$\mathrm{Nu} = 1.33\,\mathrm{Pr}^{0.362}\,\mathrm{Re}^{0.5}\{1-\exp[-3\mathrm{Pr}^{0.6}(0.0375+1.2\tau)]\}^{-1}. \quad (4)$$

Here $\tau = 2\beta\tau^*/\mathrm{Pr}$; $\beta = 3U_\infty/2R$. The Nusselt and Reynolds numbers were calculated from the properties of the gas at the outer limit of the boundary layer. The diameter of the barrier was taken as the characteristic size.

With periodic stepwise variation of the temperature, when in the course of the period T the stream temperature differs from the temperature of the surface for a k-th part of the period, the average Nusselt number is described by the expression

$$\mathrm{Nu} = 1.33\,\mathrm{Pr}^{0.362}\,\mathrm{Re}^{0.5}\left\{k+\frac{0.278\,\mathrm{Pr}^{0.6}}{T}\ln\frac{1-\exp[-3\,\mathrm{Pr}^{0.6}(0.0375+1.2kT)]}{1-\exp(-0.112\,\mathrm{Pr}^{0.6})}\right\}. \quad (5)$$

For the process under consideration the intensity of heat exchange essentially depends on the dimensionless period and can exceed the intensity of heat exchange under steady conditions for the same temperature difference between the stream and the wall. The efficiency of the intensification grows with a decrease in the Prandtl number. The frequency of pulsations of the stream temperature at which the ratio of the Nusselt numbers for the nonsteady and steady cases of heat exchange becomes greater than unity was called the critical frequency. For the adopted model it can be estimated from the equation

$$\omega_{cr} = 2.2\,\mathrm{Pr}^{0.6}\,U_\infty/R. \quad (6)$$

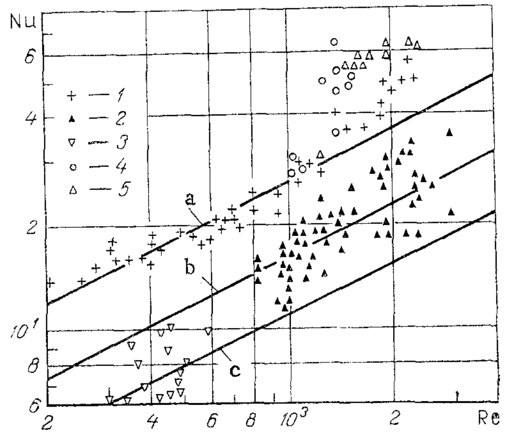

Fig. 2

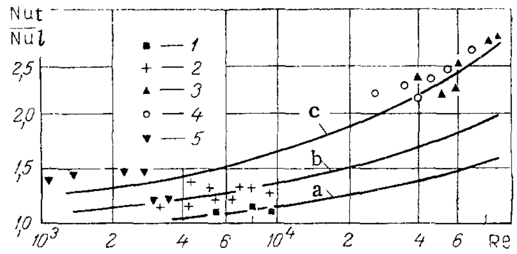

Fig. 3

Fig. 2. Influence of pulsations of the parameters of the plasma stream on heat exchange at the front point of the barrier: a–c) calculation based on the theory of Fay and Riddell [7]; 1–5) experiment; a) $Nu \cdot Re^{-0.5} = 0.85$, $h_s = 5.22$ MJ/kg; b) 0.52, 30; c) 0.36, 80; 1) [15], argon; 2–5) air; 2) h_s = 10–50 MJ/kg; 3) 50–100; 4) 24; 5) 27.

Fig. 3. Thermal action of a plasma jet on a barrier for different values of the turbulence intensity: a–c) calculation from (7); a) $\varepsilon = 0.05$; b) 0.1; c) 0.2; 1–5) experiment; 1) $\varepsilon = 0.05$; 2) 0.1; 3) [5], N_2; 4) [5], He; 5) [15], Ar; I = 77 A.

In the experiment we used a special obturation device allowing us to generate pulsations of the parameters of the plasma stream with a frequency of up to 3 kHz. With its help we investigated the influence of induced pulsations of the jet parameters on heat exchange with a barrier. The intensity of heat exchange in the investigated range of frequencies of pulsations of the parameters hardly varied within the limits of accuracy of the measurements. The critical pulsation frequency estimated from Eq. (6) was 25 kHz under the conditions of the experiments described, which is considerably higher than the frequency reached in the experiment. This may also explain the results of [6], where they found no influence of pulsations of the stream parameters due to shunting of the arc discharge in the plasmatron on heat exchange at the front critical point. In that work the frequencies of such pulsations were on the order of several kilohertz. Similar results but in an investigation of the plasma cutting of metals were obtained in [12], where they found no appreciable influence of pulsations due to fluctuations of the gas flow rate and current of the plasmatron channel on the intensity of heat transfer and removal of metal.

The experimental results of the investigation of heat exchange between a pulsating jet and a barrier, however, yield values of the ratio $\overline{Nu}/Nu_{qu.st}$ exceeding the 0.65 obtained from Eq. (5) for high values of T for the conditions of the present experiment (k = 0.65). Such an increase cannot be explained by effects connected with relaxation of the boundary layer during periodic stepwise variation of the temperature of the impinging stream. A comparison of the experimentally determined values of the Nusselt number at the stagnation point with the results of a calculation of heat exchange based on the theory of [7] shows (Fig. 2) that for the laminar flow regime the experimental data for a wide range of enthalpies (points 2 and 3) agree with the theory of Fay and Riddell. In the case of heat exchange with a pulsating jet the experimental points 4 and 5 lie above the calculated data obtained for the same degree of gas heating. This fact may be explained by the presence of turbulence in the stream. The pulsations of the stream parameters at the limit of the boundary layer do not disappear instantly but propagate in the boundary layer, causing variation of its main characteristics and the appearance of an additional heat flux.

To analyze the influence of turbulence of the impinging stream on heat exchange with a barrier in the vicinity of the stagnation point we used the empirical model of turbulent transfer of [13]. The experimental measurement of the intensity of turbulence of a high-temperature air stream was made using a double electrical probe [14]. A constant voltage was applied to two water-cooled rods with sharp points, the distance between which was 0.5–1 mm across the stream. At high stream temperatures the electrical conductivity in the gap is sufficient, and the pulsations of stream temperature can be determined from measurements of variations of the electrical resistance of the probe.

In Fig. 3 we present the results of calculations of the thermal action of a plasma jet on a barrier for different values of the turbulence intensity, as well as the experimental data of the authors [13, 15] and of [5]. The results of the numerical calculation of heat exchange are well described by the expression

$$Nu_t = Nu_l (1 + 0.044\varepsilon^{0.78} Re^{0.43}), \tag{7}$$

they are in satisfactory agreement with experiment, and they enable one to allow for the influence of the intensity of turbulence of the plasma jet in determining the heat flux to a barrier.

Thus, pulsations of the parameters of the plasma jet influence heat exchange with a barrier. In this case the increase in the intensity of heat exchange connected with reorganization of the boundary layer due to pulsations of the stream parameters with frequencies above the critical frequency or due to variation of the flow regime in the boundary layer can reach several dozen percent.

NOTATION

q, specific heat flux; I, current strength in the arc; d, diameter of plasmatron nozzle; l, relative length of the high-temperature luminous part of the jet; G, gas flow rate; R, blunting radius of barrier; τ^*, time; T, dimensionless period of temperature pulsations; β, velocity gradient; u, gas velocity; p, pressure; ε, turbulence intensity; ρ, density; μ, dynamic viscosity coefficient. Indices: 0 refers to conditions at the nozzle cut; s, at the stagnation point; w, at the wall temperature; ∞, at the outer limit of the jet; l and t refer to properties of the laminar and turbulent streams.

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DISTRIBUTION OF ELECTRON CONCENTRATION IN A DISCHARGE WITH NONUNIFORM IONIZATION OVER THE CROSS SECTION

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UDC 537.525

We have obtained an analytic solution of the charged particle balance equation for the plasma of the positive column of a discharge, with allowance for the radial variation of the ionization rate.

To find the radial distribution of the electron concentration in the positive column it is necessary to solve the particle balance differential equation with variable coefficients [1]. Solutions of this equation alone [2, 3], and also of a system of equations describing the properties of the discharge [4-7], were obtained by numerical and approximate methods. In the present article we obtain the distribution of the electron concentration by an analytic method.

We assume that the plasma of a glow discharge consists of neutral particles, singly charged positive ions, and electrons. Charged particles are formed by direct ionization, and disappear by radial ambipolar diffusion with subsequent wall recombination. The plasma is quasineutral, and the discharge parameters are uniform in the axial direction and axisymmetric. The charged particle balance for an element of volume $2\pi rR^2dr \times 1$ is described by the familiar differential equation

$$\frac{1}{r}\frac{d}{dr}\left(rD_a\frac{dn}{dr}\right)+\nu R^2 n=0. \tag{1}$$

The boundary conditions for this equation are generally written in the form

$$n(1)=0,\ \left(\frac{dn}{dr}\right)_{r=0}=0. \tag{2}$$

For a constant temperature of the gas over the cross section of the discharge chamber, as assumed in the Schottky theory [8], the coefficients D_a and ν do not depend on the spatial coordinate. Actually, there is a certain nonuniformity of the gas temperature in the radial direction which depends on the strength of the discharge, the pressure of the gas, the conditions on the boundary surface, etc. Taking account of the temperature nonuniformity of the gas leads to coefficients $D_a(r)$ and $\nu(r)$ which depend on the radial coordinate. In view of the strong dependence of the ionization rate on the ratio E/N, its relative change along the radius can exceed the corresponding change of the coefficient of ambipolar diffusion by an order of magnitude for the same nonuniformity of the gas temperature. Therefore, in the first approximation we assume that the coefficient of ambipolar diffusion is constant and equal to a certain average for the temperature range considered. We assume that the ionization rate varies parabolically with the radius $\nu = \nu_R[1 + (1 - r^2)\alpha^2]$, where α takes account of the degree of nonuniformity of the ionization rate. Then Eq. (1) is written in the form

$$\frac{1}{r}\frac{d}{dr}\left(r\frac{dn}{dr}\right)+\mu^2[1+(1-r^2)\alpha^2]n=0, \tag{3}$$

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