TRANSIENT PROCESSES OF HEAT EXCHANGE IN AN AIR–PLASMA JET

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The results of an experimental investigation of transient processes of nonsteady heat exchange in a high-temperature air stream are presented.

The data available in the literature on experimental investigations of nonsteady heat fluxes to solid walls [1, 2] often have a contradictory character. According to some data [1], the heat flux grows with time from zero to a steady value, while according to others [2] it decreases from some maximum value to a steady value. One of the possible reasons for such disagreement may be methodological errors. All the same, such experimental results have great importance in calculations of heat exchange in the process of plasma sputtering, spheroidizing, etc.

An improved method of a dynamic thermocouple [3], which makes it possible to determine the dependences of the heat flux to the wall on time ($q = q(\tau)$) and on the temperature ($q = q(T)$), as well as the temperature T_j of the gaseous phase and the local value of the coefficient of heat transfer α, in one measurement has been used to investigate heat exchange between a solid phase and a plasma stream. Moreover, because of the small size of the sensor this method has a high spatial and temporal resolution, which is especially important in the investigation of intense and rapidly occurring processes in plasma jets.

A plasmatron of axial design with gas-vortex stabilization of the arc was used to obtain the air-plasma jet. Operating parameters of the plasmatron: arc current 100 A, voltage 270 V, air flow rate $3.3 \cdot 10^{-3}$ kg/sec, average-mass enthalpy and temperature of jet 5500 kJ/kg and 3400°K, respectively. Degree of turbulence of jet 0.6-0.7.

A typical oscillogram showing the variation in the temperature of a thermocouple junction inserted into the jet with a certain frequency and its derivative (i.e., with the accuracy of a constant coefficient, the heat flux to the junction) are presented in Fig. 1. The dependence $q = q(T)$, obtained from a comparison of curves 1 and 2 of Fig. 1, is shown in Fig. 2. From an examination of these curves it follows that the entire process of heat exchange can be divided into two stages. In the first stage, called the transient process, the heat flux grows from zero to the maximum value. In the process the coefficient of heat transfer approaches infinity. In the second stage heat exchange proceeds by Newton's law.

The study of the laws of variation of the duration τ_t of the nonsteady transient process is important for an understanding of the mechanism of thermal interaction of a solid body with a plasma jet. The dependence of τ_t on the radius of the spherical thermocouple junction is presented in Fig. 3a. These data differ from the results of [4] by $\Delta \approx 0.02$ sec. The overstatement of the quantity τ_t in [4] was connected with the imperfection of the system of insertion of the thermocouple into the plasma jet. After modernization of the measurement system this error was reduced by an order of magnitude. In Fig. 3a we also present the results of a calculation of the time of the irregular heating mode, during which orientation of the heat fluxes occurs inside the solid body, according to the well-known [5] dependence

$$\tau_{ir} = B\frac{R^2}{a}, \tag{1}$$

where B is a coefficient which depends on the Biot number.

The maximum time τ_{ir} for a Chromel–Copel thermocouple, for example, does not exceed $2 \cdot 10^{-3}$ sec in accordance with (1). Therefore, to compare the character of the variation of the experimental and calculated dependences of τ_t on R on the same graph, the coefficient B in (1) was increased by 15 times. In comparing these data (Fig. 3a) one can presume that the time of the irregular mode is not decisive in the analysis of τ_t. Such a conclusion is

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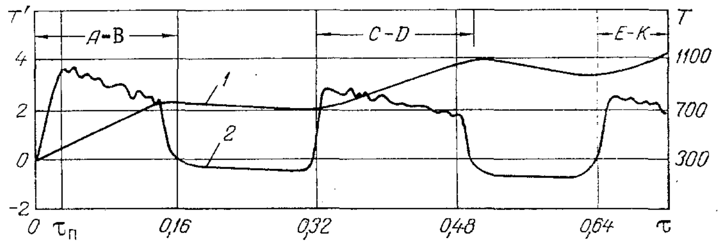

Fig. 1. Dependence of temperature of thermocouple junction (1) and its derivative (2) on time τ (sec). T, °K; $T' \cdot 10^{-3}$, deg/sec.

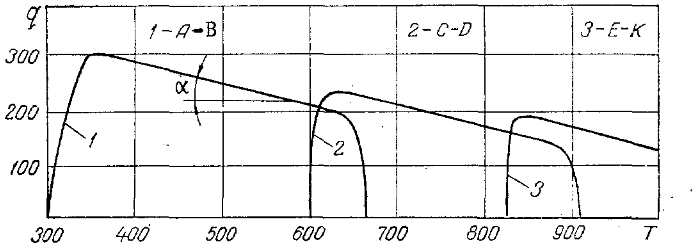

Fig. 2. Dependence of heat flux q (W/cm^2) to the thermocouple junction on its temperature T (°K). $\alpha = 0.42\ W/cm^2 \cdot deg$.

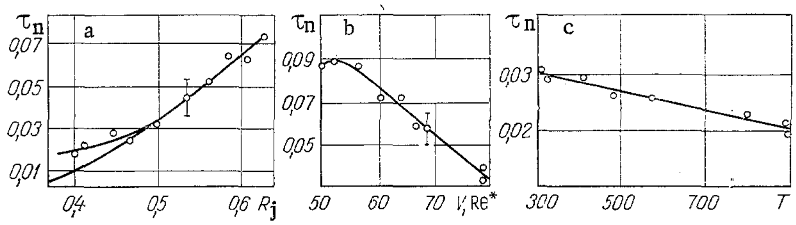

Fig. 3. a) Dependence of duration of transient process, τ_t (sec), on the junction radius R_j (10^{-3} m); b) on velocity of plasma jet, V (m/sec), and Reynolds number for the junction, $Re^* = 0.42Re$; c) on temperature of thermocouple junction, T (°K). V = 80 m/sec (a); R_j = 0.5 mm (b).

supported, first, by the fact that for $R < 0.5 \cdot 10^{-3}$ m ($Bi < 0.01$) the character of the variation of the calculated dependence differs considerably from the experimental curve and, second, by the strong dependence of τ_t on the velocity of the plasma jet (Fig. 3b). All the above allows us to assume that the quantity τ_t is conditioned mainly by the influence of the boundary layer. Such an assumption seems the more justified since τ_t depends weakly on the initial temperature T_0 of the junction (Fig. 3c). With an increase in T_0 to 1000°K, when the temperature gradient inside the thermocouple junction is practically equal to zero, the quantity τ_t comprises 0.02 sec.

The results of our investigations are in qualitative agreement with the solution of the problem of conjugate heat exchange between a blunt body and a plasma stream at the stagnation point [6]. To determine τ_t the authors of [6] recommend the dependence

$$\tau_t = \delta^2/2a, \tag{2}$$

where δ is the thickness of the dynamic boundary layer. If δ is treated as the thickness of the thermal boundary layer in (2), then the experimental results of the present work coincide with an accuracy of 30% with the calculation from (2), where $\delta = \delta_{th}$ and it is defined as [7]

$$\delta_{th} = \lambda/\alpha. \tag{3}$$

In (3) λ is taken at the gas temperature at the measurement point and α is the heat-transfer coefficient in the regular mode.

Thus, in calculations of the heating of solid bodies in a plasma jet one must allow for the nonsteadiness of heat exchange in the stage of a transient process, the duration of which depends not only on the parameters of the body but also on the properties of the plasma jet.

NOTATION

R, radius of thermocouple junction, m; a, thermal diffusivity, m^2/sec; δ_{th}, thickness of thermal boundary layer, m; λ, thermal conductivity of gas, J/m•sec•deg; α, heat-transfer coefficient, $W/m^2\cdot deg$.

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AN ANALYTICAL INVESTIGATION OF THE LONGITUDINAL TEMPERATURE PROFILE DEVELOPING DURING THE COOLING OF A CRYOGENIC PIPELINE

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Analytical expressions are obtained for the longitudinal temperature profiles of the wall and the stream of cryogen during the cooling of a cryogenic pipeline. A comparison of the calculated data with experiment gives their good agreement.

To determine the nonsteady temperature fields developing during the cooling of a pipeline one used [1] a one-dimensional description of heat transfer, it being assumed that the flow velocity of the cryogen in a given cross section is constant while the temperature only varies along the length of the pipeline.

If one neglects heat conduction of the cryogen toward the wall of the pipeline in the longitudinal direction and considers the case when the ratio of the heat capacities of the cryogen and the wall of the pipeline per unit length is small, the cooling will be described by the system of equations [2]

$$\begin{cases} (cG)_g \dfrac{\partial T_g}{\partial x} = \alpha \Pi (T_w - T_g); \\ (Fc\rho)_w \dfrac{\partial T_w}{\partial t} = \alpha \Pi (T_g - T_w) \end{cases}$$

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