TRANSIENT HEAT TRANSFER BETWEEN A SOLID AND A PLASMA STREAM

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Experiments carried out to study the transient thermal effects in the initial stage of the heating of a solid in a hot air flow are described. Preliminary results of an analysis and generalization of the experimental data are reported.

It has been noted in many studies (see, e.g., [1-9]) that the heat fluxes under unsteady heat-transfer conditions can be quite different from their steady-state counterparts. For this reason, in theory for transient thermal conditions it is necessary to solve the problem of heat and mass transfer in a boundary layer, which is related to the problem of heat transfer in the solid [1, 2]. For several complicated processes involving a thermal interaction between a solid and a hot gas flowing around it, the solution of such related problems is at present quite difficult, from both the theoretical and the computational standpoints. Under these conditions, experiments constitute our basic tool. It should be noted that in this case the requirements on the formulation and execution of the experiments, on the one hand, and on the analysis and interpretation of the experimental data, on the other, are unusually stringent.

In the present paper we report preliminary results of experiments carried out in a plasma system to study the transient thermal nature of the events in the initial stage of the heating of a solid object in a hot air flow. The electric-arc heater used to heat the air has the central-electrode geometry. The arc is stabilized by means of a magnet coil. The operating conditions correspond to an arc voltage of $U = 200$ V and a current of $I = 700$ A. The air flow rate through the nozzle is $m \simeq 0.3 \cdot 10^{-2}$ kg/sec, and the diameter of the exit cross section of the nozzle is $d_e = 0.012$ m.

Special probes with heated sensitive elements made from vacuum copper (TsMTU 3205-52) were tested (Fig. 1). The total impurity level in this material did not exceed 0.01%, so we can assume that the thermal characteristics of the sensitive elements are known highly accurately [10]. The probe construction permitted a one-dimensional temperature field in the body of the element over the test time. The thickness of the sensitive elements was varied ($b = 0.002$ and 0.05 m) to achieve a certain variation in the rate of change in the temperature in the heated surface.

The temperature at a given point in the interior of the element was measured with Chromel — Copel thermocouples with electrode diameters of $0.5 \cdot 10^{-4}$–$0.1 \cdot 10^{-3}$ m. These thermocouples were contact-welded to the body of the element. Up to six thermocouples were welded in place in each pickup; these thermocouples were spaced uniformly along a circle in a given cross section of the element or over the entire internal end surface. For the element with $b = 0.05$ m, the thermocouples were placed near the heated surface (0.002-0.003 m), so that the increase in the temperature at these points occurred at essentially the same time as the beginning of the interaction between the plasma stream and the object. The time over which a given probe could be tested was limited to the time in which the melting point of the sensitive element was reached; this time was usually 0.3-0.8 sec.

The temperature of the internal end surface of the elements with a thickness of $b = 0.05$ m did not change during the test time, so that this element can be thought of as corresponding to a model of an infinite object.

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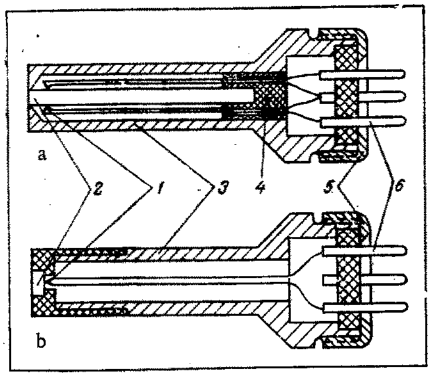

Fig. 1

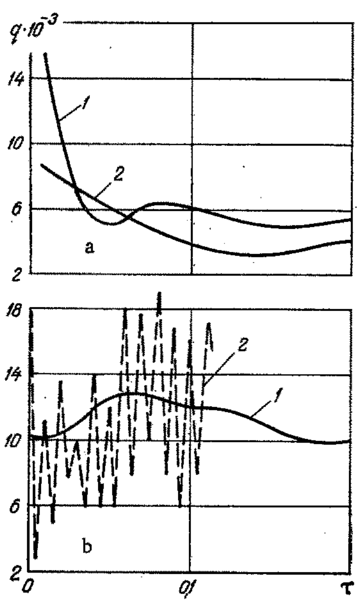

Fig. 2

Fig. 1. Probe. a) b = 0.002 m; b) b = 0.05 m. 1) Thermocouple junction; 2) sensitive element; 3) cover (type M2 copper); 4) insert; 5) nut; 6) plug-in connector.

Fig. 2. Experimental curves of the change in the heat flux q (kW/m^2) to the sensitive element of the probe over time τ (sec). a) b = 0.05 m; b) b = 0.002 m. 1) h = 0.005 m from the end of the plasmatron nozzle; 2) heat-flux function for $\alpha < \alpha_i$.

The interaction between the probe and the hot gas began when a protective shutter was opened or when the probe was inserted into the plasma stream after the apparatus had reached a steady state. The signals from the thermocouples of the sensitive elements were recorded on an N-010 loop oscillograph. From these oscillograms we obtained the measured temperatures for each thermocouple. Then we carried out a statistical analysis [11] of these data on the basis of the families of temperature curves and on the basis of the individual curves; in the course of this analysis we found estimates of the expected values and dispersions for various times. The results of this statistical analysis constituted the initial data for the construction of the unsteady boundary conditions.

To check the suggestion that a transient zone exists during the initial stage of the heating, we consider a qualitative, somewhat idealized picture of unsteady heat exchange for the cases of a thermally thick element (b = 0.05 m) and a thin plate (b = 0.002 m).

The experimental conditions corresponded approximately to a step change in the gas temperature ahead of the object at the beginning (τ_0) of the interaction of the hot gas with the solid. At this time, a thermal boundary formed at the object, and the thickness of this boundary layer increased. There is therefore a basis for assuming that the heat fluxes into the object decrease at $\tau > \tau_0$, approaching steady-state values. It can be assumed that, under identical heating conditions for both objects in the initial stage, up to time $\tau = \tau_{\mathrm{he}}$, the temperature fields in the objects are identical. The boundary of this stage, τ_{he}, is governed by the scale time for the heating of the thin plate, i.e., by the time at which the temperature at the rear surface of the plate (which we assume to be thermally insulated) begins to rise above its initial value. It can be assumed that before this time the heat fluxes into these objects are equal at any given time. After $\tau = \tau_{\mathrm{he}}$, however, the temperature distributions in these objects and the temperature gradients near the heated surface begin to be different, since the temperature equalization in the plate occurs more rapidly than in the thicker object. The temperature profiles in the thin plate at a given instant turn out to be "fuller" than in thicker elements. If we adopt this physical model, we can conclude that the rate of change of the heat fluxes into the thin plate is larger than for the thicker object.

Analysis of the experimental data confirms this assumption (Fig. 2). As the algorithms for analyzing the experimental data we used regularized schemes for solving the inverse boundary-value heat-conduction problems [12, 13], which are not restricted by a condition on the size of the calculation step. The

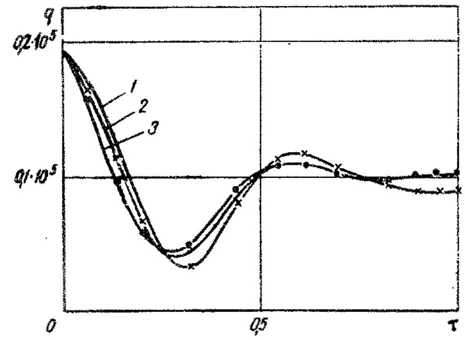

Fig. 3. Solution of a model problem; here q is in kW/m^2 and τ is in sec. 1) Given function $q(\tau)$; 2) reconstructed function $q(\tau)$ with an error level of $\delta = 10\%$ in the input data; 3) case of exact specification of the input data ($\delta = 0$).

calculations were accordingly carried out with small steps ($\Delta Fo = 0.06$), in order to distinguish possible changes in the heat fluxes into the object in the initial stage of the heating of the sensitive elements.

Analysis of these results shows that all the time dependences of the heat fluxes into the sensitive element $b = 0.05$ m thick are decreasing functions, up to a certain time. As an example, Fig. 2a shows a typical curve of the change in the heat flux for the case in which the probe lies $h = 0.005$ and 0.01 m from the end of the plasmatron nozzle. We note that at small distances from the exit of the nozzle ($h = 0.005$-0.01 m) the time derivative of the heat flux, $dq/d\tau$, at the beginning of the test of the probe is on the order of 10^5 kW/($m^2 \cdot$ sec). The transient effect has essentially disappeared by $\tau_i \simeq 0.1$ sec.

For the probes with sensitive elements $b = 0.002$ m thick, we cannot find $dq/d\tau$ and τ_i quantitatively, because of the very intense and brief transient processes. At very small values of the regularization parameter α (smaller than the values corresponding to the discrepancy principle [13-15]), however, in which case the results are oscillatory because of the incorrect formulation of the boundary-value problems (Fig. 2b), there is an abrupt decrease in the heat flux at the very beginning of the process (up to $\tau < 0.01$ sec). Because of the instrumental errors involved in the measurement, detection, and deciphering of the temperature curves, it was not possible to find any accurate value for the temperature change during this time interval.

Since the thermal processes studied here change very rapidly and are very brief, and since there are errors in the input information used in solving the inverse heat-conduction problem, we are confronted with the question of the reliability of the results. To answer this question we solved the following model problem. The heat flux into the object is specified to be

$$q(\tau) = 0.8\cdot 10^5 + \sum_{k=0}^{\infty} \frac{1}{k!}\,\frac{1}{(k+2)}\,(10\tau\sqrt{-1})^{2k}\cdot 10^5. \tag{1}$$

The nature of this curve "simulates" to some extent the $q(\tau)$ dependences obtained through the analysis of the experimental data. The calculations involved in this simulation included the solution of the direct heat-conduction problem with boundary condition (1), the "perturbation" of the temperature curves obtained from the direct problem with the help of pseudorandom-number generators [16] at an error level ($\delta = 10\%$ T_{max}) above the estimated experimental error, and, finally, solution of the inverse heat-conduction problem on the basis of these perturbed data. The results (Fig. 3) show that the algorithms used for constructing the boundary conditions are quite accurate.

It can therefore be assumed that the heat-flux behavior found through the analysis of the experimental data is quite reliable.

NOTATION

b, thickness of the sensitive element of the probe, m; τ_0, time at which the test of the probe begins, sec; τ_{he}, time over which the plate $b = 0.002$ m thick is heated, sec; τ_i, zone of the initial transient behavior, sec; ΔFo, increment in the Fourier number; h, distance of sensitive element of probe from end of the plasmatron nozzle, m; α_i, regularization parameter corresponding to the discrepancy principle; q, heat flux into the object, kW/m^2; T_{max}, maximum value of the temperature curve under discussion, deg; δ, error level of the input data, as a percentage of T_{max}.

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