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NEW METHOD FOR NONSTEADY-HEAT-TRANSFER INVESTIGATIONS IN A THERMAL AERODYNAMIC TUBE

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A new method of thermal testing and processing the resulting data is developed on the basis of Tikhonov's regularization method. Nonsteady heat transfer is investigated on an elongated model.

A new method of treating the results of thermal tests in an aerodynamic tube has been developed recently [2, 3] based on A. N. Tikhonov's regularization technique for the solution of inverse heat-conduction problems. This method can be used for heat-transfer investigations in significantly nonsteady conditions and hence, in contrast to existing thermal-testing methods using regular heating conditions, it is unnecessary to wait some time after tube startup so as to ensure that the model is introduced into steady flow. The model may be introduced into the working part of the tube earlier, and flow with a uniform field over practically the whole of the characteristic rhomb of the nozzle may be used. As a result, a comparatively small working part of the tube may provide a large value of Re, calculated over the length of the model, corresponding to transient and turbulent states of the boundary layer.

In the present work, heat-transfer experiments were carried out in a supersonic ($M = 5.0$) aerodynamic tube with an axisymmetric nozzle of diameter 0.29 m. The model (Fig. 1) was in the form of a tapering hollow cylinder (length 1.15 m; diameter 0.04 m; wall thickness 0.002 m) of 1Kh18N9T stainless steel. To allow heat-flux measurements at two cross sections of the model (I, $x = 0.3$ m from the nozzle; II, $x = 1$ m from the nozzle), Chromel—Alumel thermocouples of thickness 0.0002 m were welded to the inside of the model wall. The model was attached to a fixed mount in the tube. The tests were carried out for unsteady conditions of tube operation, associated with tube startup and with transient processes due to temperature variations of the incoming flow (between 300 and 500°K). The pressure in the tube antechamber was held constant ($P_{0a} = 8 \cdot 10^5$ N/m^2) by means of an automatic choke. The gas-flow stagnation temperature was recorded using a thermocouple assembly in the tube antechamber. The thermal inertia of the thermocouple assembly was determined experimentally and taken into account in the analysis of the test results by an appropriate correction in the test-result processing program.

The test results were processed by numerical methods using an algorithm for the solution of the one-dimensional linear inverse heat-conduction problem. In this case, the unsteady heat flux $q(\tau)$ at the surface of the model is determined by an integral Volterra equation of the first kind:

$$f_\delta(\tau) = \int_0^\tau q(\xi) K(\tau, \xi) d\xi,$$

where $f_\delta(\tau)$ is a known function of the initial delta. For a plane plate with a heat-insulated inner wall and constant initial temperature,

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$$f_\delta(\tau) = T(\tau) - T(0),$$

$$K(\tau, \xi) = \frac{a}{\lambda R}\left\{1 + 2\sum_{n=1}^{\infty} \exp\left[-a\left(\frac{\pi n}{R}\right)^2 (\tau - \xi)\right] \cos\frac{\pi n x}{R}\right\}.$$

The function $q(\tau)$ is found as an extremum of the regularizing functional

$$M^{\alpha^*}[q] = \int_0^{\tau_m} \left[\int_0^{\tau} q(\xi) K(\tau, \xi) d\xi - T(\tau)\right]^2 d\tau + \alpha^* \int_0^{\tau_m} [q'(\xi)]^2 d\xi$$

and is determined by the well-established system of linear algebraic equations [2]

$$\sum_{k=1}^{m} p_{l,k} q_k = f_l, \quad l = 1, 2, \ldots, m,$$

where

$$p_{k,k} = h^4 \sum_{i=k}^{m} A_i [K_{i,k}]^2 + \alpha^*, \quad k = 1, \ k = m,$$

$$p_{k,k} = h^4 \sum_{i=k}^{m} A_i [K_{i,k}]^2 + 2\alpha^*, \quad k \neq 1, \ k \neq m,$$

$$p_{k,k+1} = h^4 \sum_{i=k+1}^{m} A_i K_{i,k} K_{i,k+1} - \alpha^*, \quad k = 1, 2, \ldots, m-1,$$

$$p_{l,k} = h^4 \sum_{i=k}^{m} A_i K_{i,k} K_{i,l}, \quad k \geqslant l + 2,$$

$$p_{l,k} = p_{k,l}, \quad l, k = 1, 2, \ldots, m,$$

$$f_l = h^3 \sum_{i=l}^{m} A_i K_{i,l} T_i, \quad l = 1, 2, \ldots, m.$$

The regularizing parameter α^* is chosen by matching the discrepancy with the error of the initial data. When the information on the measurement error is inadequate, it is expedient to use the quasioptimal-parameter method in conjunction with solution of the direct problem on the basis of the observed heat flow, comparing the results with experimental data.

To solve this problem on a BÉSM-6 computer, a program was written in FORTRAN with graphical display of the results. Cubic curves were used in interpolating the results.

The purpose of the tests was twofold. First, it was necessary to establish the effectiveness of the new thermal-testing method in the more complicated conditions of nonsteady heating of the model and, second, it was required to investigate transient conditions of aerodynamic-tube operation in terms of the parameters characterizing heat transfer. Transient conditions are of interest not only for their own sake but also because they may be associated with the nonreproducibility of experimental heat-transfer data obtained by the regular-heating method in this tube, which has yet to be satisfactorily explained. The characteristic feature of this aerodynamic tube is that the air is heated before it reaches the antechamber by means of fuel combustion in the air flow and, depending on the chosen conditions of preheating, evidently, different degrees of turbulence may appear in the flow at the nozzle output. Therefore, two very different transient conditions were investigated. The tests were carried out for fast and smooth transitions to steady tube operating conditions in terms of the stagnation temperature; the pressure in the antechamber and the volume output from the nozzle were held constant in all cases.

The test results are shown in Figs. 2-4, in the form of curves of the variation with time in the stagnation temperature in the antechamber $T_0(\tau)$, the temperature of the internal model wall $T(\tau)$, the heat-flux density $q(\tau)$ determined by numerical solution of the inverse heat-conduction problem, and the heat-transfer coefficient

$$\alpha(\tau) = \frac{q(\tau)}{T_0(\tau) - T_w(\tau)}.$$

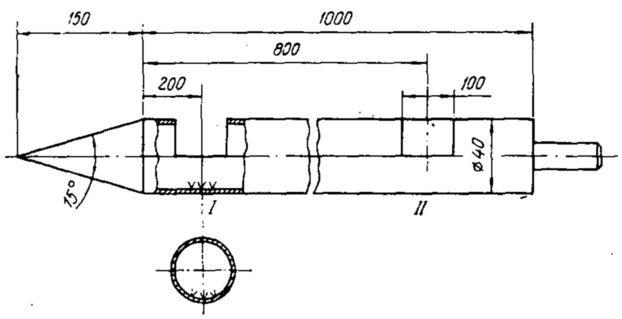

Fig. 1

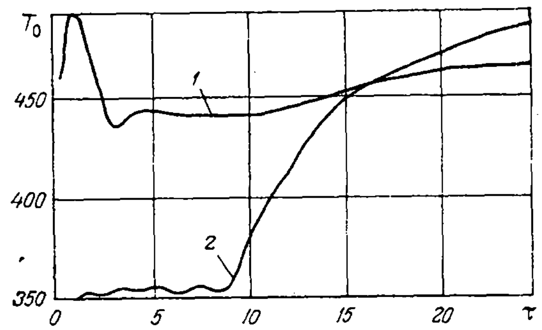

Fig. 2

Fig. 1. Diagram of model.

Fig. 2. Stagnation temperature vs time: 1, 2) different tube-startup conditions.

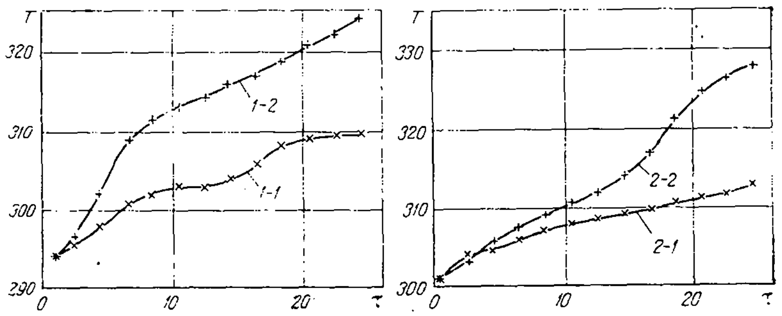

Fig. 3. Temperature of internal model wall vs time: the first figure corresponds to the startup conditions and the second gives the cross section.

The surface temperature $T_W(\tau)$ is found from the solution of the direct problem in terms of the recovery of the nonsteady temperature field of the plate.

The number Re_x calculated from the stagnant-flow parameters is $4 \cdot 10^6$ and $1.3 \cdot 10^7$ for the two test cross sections of the model, i.e., corresponds in the first case to a laminar and in the second to a turbulent boundary layer. The theoretical values of the heat-transfer coefficient given by the formulas recommended in [4] for these values of Re_x are $\alpha_{1l} = 11.3$ and $\alpha_{2T} = 60.6$ W/m$^2 \cdot$°K, respectively. As is evident from Fig. 4, because of its great length, the model supports both laminar and turbulent boundary layers. The steady experimental values of the heat-transfer coefficients are in good agreement with the theoretical values. The reproductibility of the experimental results in steady heat-transfer conditions is ±5%.

It is evident from Figs. 2-4 that the heat-transfer coefficient changes considerably during the transient phase of tube operation. In the first seconds of the experiment α is very large; it then rapidly decreases and tends to a constant value after approximately 2-5 sec for the fast transient conditions and about 13-15 sec for the smooth transient conditions. The extremely intense heat transfer in the first few seconds of the experiment remains to be explained. It may be associated with the combustion of fuel that accumulates in the flow part of the tube before it ignites, because of ignition lag; this is often observed when the preheating is maintained at low temperatures, i.e., when the flow rate is small and hence the fuel dispersion is poor. These are precisely the conditions that arise in the case of the smooth transient conditions. Note that, after stable flame-combustion conditions are reached in the preheater, further regulation of the flame temperature is not accompanied by any marked deviation of the heat-transfer coefficient from the steady value.

Thus the experimental results show that the new method of thermal testing, using numerical treatment of the experimental results, not only extends the experimental uses of existing aerodynamic tubes but also provides the basis for a new approach to the improvement of thermal-testing quality and accuracy.

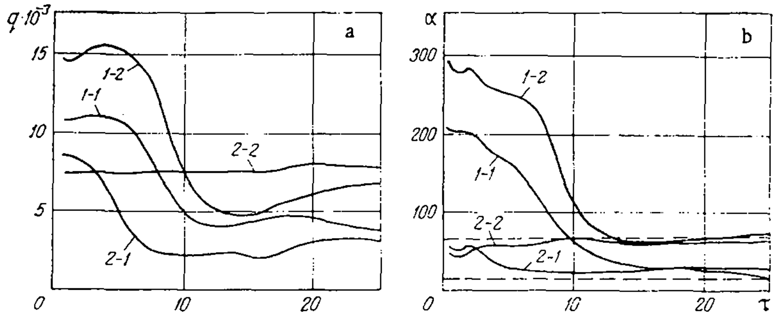

Fig. 4. Heat-flux density (a) and heat-transfer coefficient (b) vs time: the first figure corresponds to the startup conditions and the second gives the cross section.

NOTATION

M, Mach number; Re, Reynolds number; P_0, stagnation pressure; T_0, stagnation temperature; T_w, temperature of external model surface; T, temperature of internal model surface; q, unknown heat flux; τ, time; τ_m, time of process; α^*, regularization parameter; a, thermal diffusivity; λ, thermal conductivity; α, heat-transfer coefficient; R, thickness of model wall.

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NONSTEADY FLOW OF DISSOCIATING NITROGEN TETROXIDE IN A STEAM-GENERATING CHANNEL

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A one-dimensional conjugate model is proposed for the nonsteady flow of chemically reacting nitrogen tetroxide in a steam-generating channel and the boundaries of hydrodynamic stability are investigated.

1. Mathematical Model

The conjugate nonsteady problem of a flow of chemically reacting heat carrier — nitrogen tetroxide (N_2O_4) — in a steam-generating channel is investigated. In formulating the mathematical model of the two-phase flow, the steam-generating channel is considered as a system with distributed parameters, using integral characteristics such as the heat-transfer, slip, and friction coefficients, the mean flow vapor content taken over the channel cross section, and the mean-mass flow rate. The system of one-dimensional nonsteady equations describing the behavior of the induced N_2O_4 flow is complemented by the nonsteady heat-conduction equation for the channel wall.

For a more complete description of the induced two-phase flow in the channel, the channel is divided into five regions differing in conditions of motion, heat-transfer mechanisms, and the balance of dissociation in the system $N_2O_4 \rightleftharpoons 2NO_2 \rightleftharpoons 2NO + O_2$.

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