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A METHOD OF PROCESSING THE READINGS OF A GRAPHITE CALORIMETER

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A quasi-solution method has been applied to a nonlinear inverse problem in thermal conduction to process test data for a graphite calorimeter in a plasma jet.

Inverse problems in thermal conduction occur in experimental aerodynamics, particularly for heat transfer to models in wind tunnels, e.g., in relation to the testing of thermal shields and high-temperature constructional materials. These inverse problems have to be considered when it is necessary to calculate the temperature pattern in a model while the parameters of the external flow and the boundary conditions are not well established, e.g., in measurements on the nonstationary heat transfer from a high-temperature jet. A graphite calorimeter is used for the purpose here.

The calorimeter (Fig. 1) is a cylindrical graphite vessel having a flat bottom, into which is screwed a sensitive element of thickness 0.017 m and diameter 0.04 m. There are three Chromel–Alumel thermocouples of thickness 8×10^{-5} m inserted in the sensitive element near the center on the inside. The thermocouples are attached by contact welding to a layer of zirconium of thickness 10^{-4} m melted onto the graphite in a vacuum furnace.

The solution of the inverse problem for the graphite is complicated because the parameters are very much dependent on temperature, so the treatment is nonlinear. A stable solution is found by the quasisolution method [1-3]. One has to determine the heat-flux density from the temperature variation at the internal surface, which involves a nonlinear problem in thermal conduction for a one-dimensional wall in the following formulation: one is given a parametric compact family K of functions $q(\tau)$, from which one selects a time function for the heat flux $q_w(\tau)$ such that the theoretical time function for the temperature $T_t(\tau)$ at the internal surface of the wall corresponds best with the measured result $T_m(\tau)$, i.e., $q_w(\tau)$ is defined by the condition

$$\max_{0\leqslant\tau\leqslant\tau_{max}} |Aq_w(\tau) - T_m(\tau)| = \inf_K \max_{0\leqslant\tau\leqslant\tau_{max}} |Aq(\tau) - T_m(\tau)|,$$

where A is the finite-difference operator for the direct nonlinear thermal-conduction problem:

$$Aq(\tau) = T_t(\tau), \quad 0 \leqslant \tau < \tau_{max}.$$

The uniformly bounded and equally continuous parametric families of functions are compact in the space of continuous functions with a uniform-approximation metric. The heating conditions are close to those of regular modes, so the compact set is taken as a two-parameter family of exponential functions:

$$K \equiv \{q(\tau) : q(\tau) = Q\exp(-m\tau), \quad Q_{min} \leqslant Q \leqslant Q_{max}, \quad m_{min} \leqslant m \leqslant m_{max}\}.$$

The choice of the set in this form is justified by the good agreement between the theoretical result $T_t(\tau)$ and the measured one $T_m(\tau)$ (Fig. 2).

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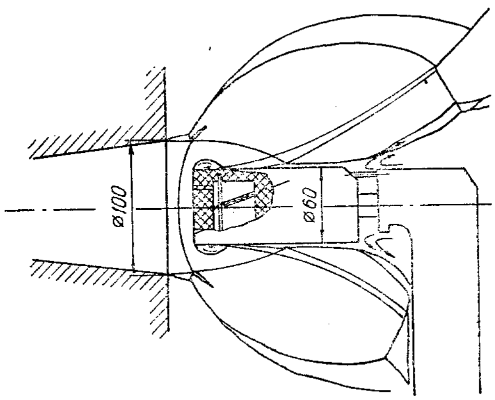

Fig. 1. Graphite calorimeter.

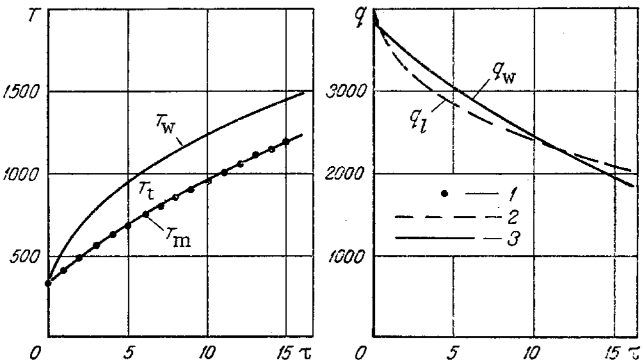

Fig. 2. Test results for the graphite calorimeter: 1) experiment; 2) calculation in accordance with [4, 5]; 3) inverse-problem solution; M = 5.0, T_0 = 3150, P_0 = 50.2 × 10^5.

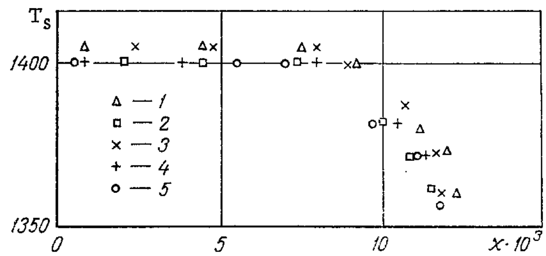

Fig. 3. Temperature distribution on the side surface at successive instants: 1) τ = 1.5; 2) 3.5; 3) 5.5; 4) 7.5; 5) 9.5 sec.

The tests on the graphite calorimeter were performed in a high-temperature wind tunnel with an Eifel chamber in the free jet emerging from a conical nozzle of diameter 0.1 m with M = 4.95-5.5, which gave jet flow around the calorimeter with a conical unperturbed flow as shown schematically in Fig. 1.

The calorimeter was inserted into the steady-state jet by means of a movable holder. The tests were performed under two sets of working conditions involving different pressure (P_0 = $6 \cdot 10^5$ and $55 \cdot 10^5$ Pa) and temperature (T_0 of 1500 and 3300°K), which differed in heat-flux density at the shock-wave point by about a factor of 2.7. We tested 12 calorimeters. The test results were reproducible within 96%.

Figure 2 shows the variation in T_m in one of the experiments together with the calculated values for T_w for the outer surface of the sensitive element and the heat flux at q_w; for comparison, we give the heat-flux density at the shock-wave point q_l calculated on the basis of the actual parameters of the air [4, 5]. Figure 2 shows that the measured heat flux at the end of the graphite calorimeter is in satisfactory agreement with the calculation for a laminar boundary layer.

In some of the experiments, the temperature measurement by means of the thermocouples was accompanied by measurement of the temperature T_s on the surface of the calorimeter by an optical method [6], with recording of the spectrum with the Infra 780A plates, whose peak sensitivity is in the range 7×10^{-7} to 8×10^{-7} m. In that case, the intensity of the radiation from the gas is much weaker than that from the surface. The results for T_s from one run in relation to x at successive instants $\tau = 1.5; 3.5; 5.5; 7.5; 9.5$ sec are shown in Fig. 3. These measurements show that there is a peak in the heat flux at the side surface, which appears to be due to a local area of detached flow (Fig. 1).

This one-dimensional inverse treatment for the graphite calorimeter is not applicable to turbulent heat transfer at a flat end, where the heat-transfer coefficient increases in accordance with a power law along the radius.

NOTATION

M, Mach number for incoming flow; T, temperature; q, heat flux; α, heat-transfer coefficient; τ, current time; x, longitudinal coordinate. Subscripts: 0, isentropic stagnation; w, wall; m, measured; s, side surface; l, laminar; t, theoretical.

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SMOOTHING SPLINES APPLIED IN THERMAL EXPERIMENTS

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Cubic smoothing splines are applied to heat transfer in a region of detached flow on a plate with a cylindrical obstacle.

The heat flow in the region around a cylindrical obstacle in a supersonic flow has been examined [1, 2] by means of thermal indicator coatings for models made of insulating material. It has been found that the longitudinal distribution of the heat flux $q(\bar{x})$ along the axis of symmetry of the model is of peaky type in this region.

The numerical method employed here for processing the results incorporates the nonstationary and two-dimensional characteristics of the heating, so it was possible to perform the study in an ordinary wind tunnel (with $M_\infty = 6.0$) on a model with a thin wall ($\delta = 10^{-4}$ m) made of conducting material fitted with thermocouples (Fig. 1). The number of thermocouples was raised to seven per 10^{-3} m [3, 4] in the region where the heat flux varied considerably. In the tests, the model was inserted rapidly (in 0.075 sec) into the flow. The readings from the thermocouples were recorded with high-sensitivity apparatus working with a light-beam oscillograph [5].

Figure 2a shows the longitudinal temperature distribution $t(\bar{x})$ along the symmetry axis $\bar{x}$ of the model at successive instants ($\bar{x} = x/d$, where $d = 3 \cdot 10^{-3}$ m is the diameter of the cylinder, while the axis of the cylinder passes through $\bar{x} = 0$, and the incident flow is directed from right to left).

The heat fluxes were computed with a BÉSM-6 computer from the measured temperature distribution $t(x, \tau)$ on the assumption that the wall was thin and with allowance for the heat leakage in the x direction:

$$q(x,\ \tau) = \delta \left(\rho c\ \frac{\partial t}{\partial \tau} - \lambda\ \frac{\partial^2 t}{\partial x^2} \right)$$

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