USE OF AN ELECTRONIC COMPUTER TO DETERMINE THE HEAT FLUX BY MEANS OF THE NONSTATIONARY TEMPERATURE FIELD AT THE NOZZLE WALL

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A method to determine the heat flux in a nozzle at stream temperatures above the nozzle wall melting point is elucidated. An experimental distribution of the local heat flux along the nozzle contour is presented.

One of the most stressed elements of a hypersonic wind tunnel is the nozzle. Up to now there have been no reliable methods of measurement and, consequently, no methods to compute the thermal loads in nozzles at stream stagnation temperatures above 1500°K. Technical difficulties of investigating heat exchange in nozzles are associated with the need to measure variable heat fluxes along the length of a nozzle whose inner contour should certainly be smooth. Disposition of sensors on the inner nozzle surface or use of heat-insulating spacers should be eliminated, since the flow field and the heat-flux distribution are hence distorted.

To investigate the local heat exchange, a copper conical supersonic nozzle with a smooth subsonic entrance section was fabricated. A cylindrical section with 7 mm diameter and 47 mm length was disposed in the zone of the critical section with a conical part with a 4° half-angle following it. The nozzle outer diameter was 75 mm. By using deep 3-mm-wide circulators, the nozzle was divided into sections by an 11- and a 22-mm-wide ring (Fig. 1). The bulky rings were heat accumulators and increase the wall heating time. The wall is heated to a higher temperature at the crosspieces, which hinders heat overflow along the nozzle contour. Taking symmetry conditions into account, half an element consisting of two cylinders can be considered as a calorimeter insulated from the other rings.

Chromel–Copel thermocouples, whose readings were recorded on an oscillograph, were fixed at different points of each element. The depth of fixing the thermocouples was determined by means of the depth of the prepared hole. The thermocouples were fastened by using the pressing of cylindrical copper plugs [1].

The inverse problem of nonstationary heat conduction was solved in processing the test results, i.e., the heat flux on the heat-receiving surface is reproduced by means of the measured change in temperature. To do this, the two-dimensional heat-conduction equation

$$\frac{\partial t}{\partial \tau} = a\left(\frac{\partial^2 t}{\partial r^2} + \frac{1}{r}\cdot\frac{\partial t}{\partial r} + \frac{\partial^2 t}{\partial x^2}\right)$$

under the following boundary conditions: the heat flux depends only on the time for $r = R_1$ and $0 \le x \le x_1$, hence

$$\alpha(T_{\mathrm{ad}} - T_w) = -\lambda\frac{\partial t}{\partial r}.$$

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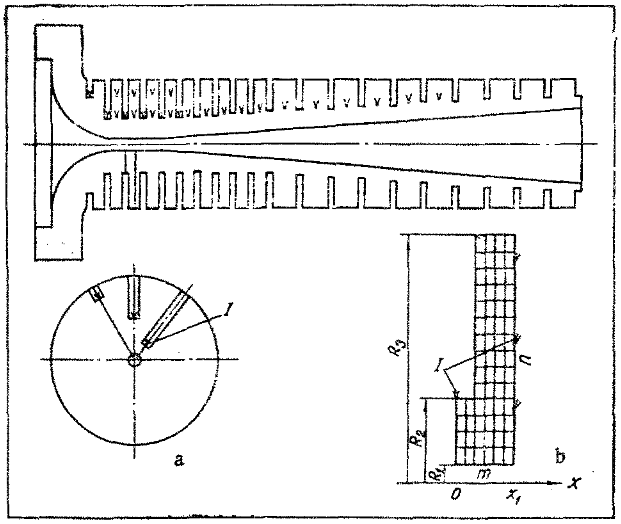

Fig. 1. Diagram of the experimental nozzle: a) diagram of thermocouple location; b) typical computing element; I) thermocouple.

was solved in application to an isolated element by the heat-balance method. All the remaining boundaries of the isolated annular element are heat insulated. The body temperature is constant at all points at the initial instant. The coefficients of thermal diffusivity a and thermal conductivity λ are constant.

The temperature at the point where the thermocouple is fixed was determined at a given time τ as a result of solving the equation and was compared to the measured temperature which had first been inserted into the memory of the BÉSM computer. If the coordinate where the thermocouple had been fixed did not coincide with the node of the partition mesh where the temperature was calculated, linear interpolation was introduced. When the temperatures did not agree, a correction to the heat-exchange coefficient was introduced by means of the formula

$$\alpha_{i+1} = \alpha_i + \frac{t - t_i}{t_i - t_{i-1}} (\alpha_i - \alpha_{i-1}),$$

where i is the number of the iteration, and the computation was repeated until the temperatures agreed to a given accuracy $t - t_i < \varepsilon$. The last value of the coefficient α was taken as the actual value at the time τ_i. The value of the temperature hence obtained at the computational nodes of the calorimetric element was taken as the initial value for the computation of the temperature at the end of the next time spacing. The temperature was determined at 1-sec intervals.

The accuracy of the heat-balance method depends on the number of partitions, m, n per volume element along the x and r axes. For m = 6 along the x axis (Δx = 0.75 mm), the passage from n = 7 to n = 14 along the r axis (Δr = 5 and 2.5 mm) resulted in a 2.5% change in the heat-exchange coefficient. Hence, there was no further increase in the number of computational points.

The accuracy of giving the temperature curve and the influence of a random temperature perturbation on the results of determining the heat-exchange coefficient were verified. For a temperature given as a smooth curve and the temperatures in agreement to ε = 0.5 and 0.1° accuracy, the difference between the coefficients α did not exceed 0.5-1%. For temperatures given with a ±3° difference from the smooth curve, the heat-exchange coefficients were determined with a ±10% deviation from the mean value. The influence of a random perturbation of the temperature given by the smooth curve on the next value of the coefficient α extended over 1-2 time intervals. Hence, outstanding points must be eliminated in processing the experimental data.

A total of three-four iterations are sufficient to determine the heat-exchange coefficient when there is a substantial difference between the initial and final heat fluxes and agreement between the temperatures to ε = 0.1 accuracy. A direct check on the validity of carrying out the calculations is a comparison between the temperatures measured at various points of the calorimeter element and those calculated by means of the heat flux found from readings of one of the thermocouples.

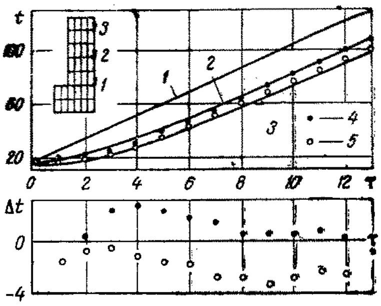

Fig. 2

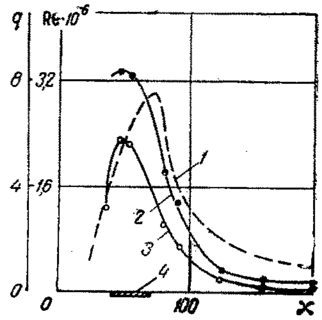

Fig. 3

Fig. 2. Temperature distribution in a typical nozzle element (t is the temperature, °C; τ is the time, sec; Δt is the temperature difference, deg, between the computed and experimental temperatures at the points 2 and 3; curves 1-3) computed curves of the time variation of the temperature at points where the thermocouples 1-3, respectively, are fixed; 4-5) experiment).

Fig. 3. Reynolds number Re and heat flux q, MW/m^2, distributions along the nozzle x, mm: 1) Reynolds number; 2) heat flux, $p_0 = 37$ bars; 3) heat flux, $p_0 = 27$ bars; 4) cylindrical nozzle section.

Presented in Fig. 2 are results of a computation and measurements which show that the difference between the measured and calculated temperatures does not exceed 3°. The heat flux was calculated by means of thermocouple No. 1, closest to the heated surface.

Shown in Fig. 3 are the heat-flux and Reynolds-number distributions along the nozzle axis for a total pressure of $p_0 = 37$ and 27 bars in the prechamber at a temperature $T_0 = 1700$°K at the time $\tau_1 = 6$ sec. The maximum heat flux in the critical nozzle section reached 8.0 and 5.6 MW/m^2, respectively. Measurements showed that despite the presence of a cylindrical section more than 6 calibers long, the heat flux in the zone of the critical section is variable and has a definite maximum which does not agree with the position of the maximum Reynolds number.

NOTATION

t, temperature; τ, time; r, x, cylindrical coordinates; R_1, inner radius; α, a, λ, coefficients of heat-exchange, thermal diffusivity, and thermal conductivity, respectively; T_{ad}, temperature of the adiabatically decelerated gas; T_W, wall temperature at $r = R_1$; p_0, total gas pressure; q, specific heat flux.

LITERATURE CITED

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