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EXPERIMENTAL INVESTIGATION OF LOCAL HEAT TRANSFER IN A TURBULENT BOUNDARY LAYER AT SUPERSONIC SPEED

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The authors present results of an experimental investigation of coefficients of local heat transfer in a turbulent boundary layer over a wide range of M and Re numbers and values of the temperature ratio.

Most of the presently known methods of calculating convective heat transfer in a turbulent boundary layer at supersonic speeds are based on experimental data. However, these data span heat-transfer conditions rather fully only for comparatively low Reynolds numbers and for surface temperatures close to adiabatic. There has been little experimental study of the influence of large Reynolds numbers over a wide range of values of temperature ratio and Mach number.

The aim of the present investigation is to obtain the heat-transfer laws in a turbulent boundary layer over a wide range of the governing criteria. The tests were made in a wind tunnel on airfoil models with a 5% profile and a cylindrical body of revolution with ogive nose section and length equal to 4. The experimental values of local heat-transfer coefficients span the ranges $Re_\delta = 2.5 \cdot 10^6$–$84 \cdot 10^6$, $M_\delta = 1.8$–6.2 and temperature ratio $\overline{T}_w = T_w/T_r = 0.28$–$1.37$.

To obtain values of the temperature ratio $\overline{T}_w < 1$ on the model surface we used special equipment to cool the model skin with a mixture of liquid and gaseous nitrogen and to maintain its temperature at a given level. The flow rate of liquid nitrogen was determined from the condition of obtaining a given average temperature on the model surface, and the gaseous flow rate was determined by the need to maintain rather high flow velocities of two-phase mixture in the internal channels of the model to avoid separation of the liquid phase.

To measure local heat-transfer coefficients with $\overline{T}_w > 1$, we heated the model prior to the test by means of a special electrical heater. In the tests with hot flow ($M_\delta = 6.2$) the model was heated immediately before the flow was brought on.

The surface temperatures and the local heat-transfer coefficients were measured by means of special thermal sensors located on the inner surface of the model skin [1]. With these one can measure local heat-transfer coefficients to the model surface by both steady and unsteady methods. The total error in determining local heat-transfer coefficients did not exceed 15%.

The test heat-transfer data were reduced to obtain a power-law relationship between the governing criteria of the form

$$St_\delta = A Re_\delta^n (1 + 0.2 r M_\delta^2)^m \left(\frac{T_w}{T_r}\right)^k,$$

where A, n, m, and k are constants; r = 0.89 is the flow temperature recovery factor.

In determining the Reynolds number one must know the conditions of boundary-layer development. The test models had a pressure gradient and therefore the conditions differed from flow over a flat plate, which made it difficult to compare the results of different experiments directly, and therefore the flow conditions for the test models were reduced to conditions for flat plate flow.

We allowed for the influence of the pressure gradient on the development of the boundary

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layer by choosing an effective length in defining the Reynolds number, which we found as follows. The wetted surface of the model was divided into a number of stepwise sections. The flow over each section was considered as gradient-free flow with the known value of the flow parameters. The Reynolds number on the first section was determined from the local flow parameters on each section and the length reckoned from the nose or the model leading edge, and the Re number on the second section was calculated from the local flow parameters and the effective length, taking account of the prehistory of boundary-layer development in the first section. The effective length was found from the condition that the momentum loss thickness in the boundary layer should remain unchanged at the point of transition from the first section to the second, etc. The method of determining the effective length was described in detail in [2].

We allowed for small sections with laminar boundary layer on the models by determining the effective start of the development of the turbulent boundary layer. To determine this we subtracted the length of the laminar section from the total length from the nose or the leading edge of the model to the section considered, and applied a correction Δx obtained from the condition that the momentum loss thickness be equal for the laminar and turbulent boundary layers at the start of the transition region [3], whose location was determined from the nature of the variation with model length of the local heat-transfer coefficients.

Thus, the Reynolds number values were determined from the local flow parameters at the outer edge of the boundary layer, found by calculation, and the effective length of the fully turbulent flow on a flat plate, determined with allowance for the pressure gradient on the models and the existence of laminar sections.

The model skin temperature T_w was determined as the arithmetic mean of the temperatures measured on the model. In all regimes of wind tunnel operation we obtained quite a uniform temperature field on the models. For example, with $\overline{T}_w \approx 0.3$, which corresponds to cooling of the skin to the boiling temperature of liquid nitrogen, the deviation of the temperature from its mean value did not exceed 5°. With increase of the surface temperature, the uniformity of the temperature field became somewhat worse.

From the reduced test data we evaluated the influence Re_δ, and M_δ numbers and the temperature ratio $\overline{T}_w$ on the local heat transfer. The method of reducing the experimental data was as follows.

The test values of local heat-transfer coefficient were first expressed as a logarithmic dependence on the temperature ratio T_w/T_r for fixed values of Re_δ and M_δ numbers, and the influence of this ratio on the heat transfer was determined. In the range of T_w/T_r investigated this influence is described quite well by the relation $St_\delta \sim (T_w/T_r)^{-0.24}$. Then we found the influence of the M_δ number on the heat transfer. The experimental data were reduced in the form of the dependence of the product $St_\delta \overline{T}_w^{0.24}$ on the parameter $(1 + 0.178\ M_\delta^2)$ at a fixed value of the Reynolds number. The test points obtained for all the M_δ numbers investigated and all values of the temperature factor $\overline{T}_w$ lie on the straight line $St_\delta \overline{T}_w^{0.24} \sim (1 + 0.178\ M_\delta^2)^{-0.47}$ [2].

To determine the influence of the Re_δ number, the test results were expressed in the form of a logarithmic dependence of the product $S = St_\delta \overline{T}_w^{0.24}\ (1 + 0.178\ M_\delta^2)^{0.47}$ on the Re_δ number (Fig. 1a). For the entire range of M_δ, Re_δ, and $\overline{T}_w$ values investigated, the test points group quite well about a straight line. After processing the test-point scatter by the least-squares method we obtained the equation for this line

$$St_\delta \overline{T}_w^{0.24} (1 + 0.178\, M_\delta^2)^{0.47} = 0.028\, Re_\delta^{-0.18}.$$

Figures 1b, c show the influence of the temperature ratio $\overline{T}_w$ and the M_δ number on the local heat transfer for all the experimental points, in the form of the dependence of the product $K = St_\delta Re_\delta^{0.18}\ (1 + 0.178\ M_\delta^2)^{0.47}$ on $\overline{T}_w$ and of $N = St_\delta Re_\delta^{0.18} \overline{T}_w^{0.24}$ on the quantity $(1 + 0.178\ M_\delta^2)$. Processing of the points by the least-squares method confirmed the correctness of the exponents obtained for the governing criteria $\overline{T}_w^{-0.24}$ and $(1 + 0.178\ M_\delta^2)^{-0.47}$.

In these tests the range of variation of temperature T_δ was not enough to investigate its influence on the heat transfer. However, we can estimate its influence by introducing the factor $(T_\delta/100)^{-0.054}$, describing the variation of air viscosity with expansion of the range of temperature T_δ.

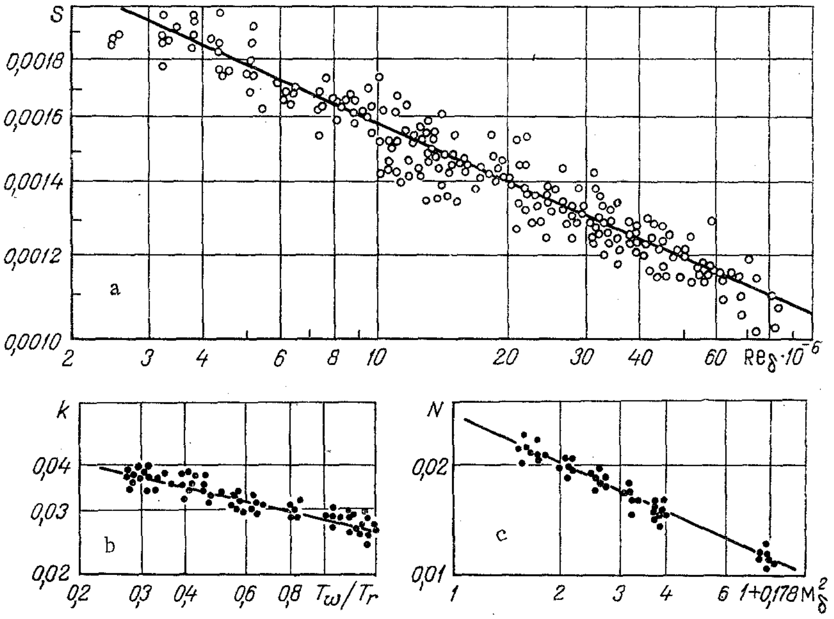

Fig. 1. The dimensionless heat-transfer coefficient as a function of: a) the Reynolds number $S \sim Re_{\delta}^{-0.18}$; b) the temperature ratio $\bar{T}_w$ $K \sim (T_w/T_r)^{-0.24}$; c) the M_δ $N \sim (1 + 0.178M_{\delta}^2)^{-0.47}$

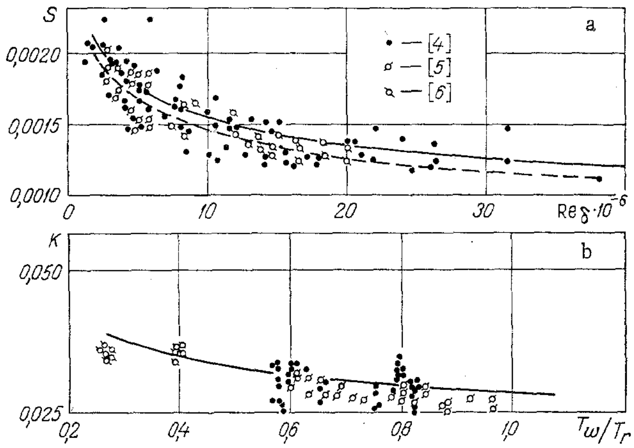

Fig. 2. Comparison of the results obtained with available experimental data as a function of Re_δ number (a) and temperature ratio $\bar{T}_w$(b).

Thus, by processing the experimental data we obtained an empirical formula for calculating local heat-transfer coefficients in a turbulent boundary layer, reduced to the conditions on a flat plate:

$$St_\delta = \frac{\alpha}{\rho_\delta v_\delta c_p} = 0.028\, Re_\delta^{-0.18} (1 + 0.178\, M_\delta^2)^{-0.47} \left(\frac{T_w}{T_r}\right)^{-0.24} \left(\frac{T_\delta}{100}\right)^{-0.054}. \quad (1)$$

Figure 2 compares the results obtained with test data on heat transfer in a turbulent boundary layer in the range of numbers $M_\delta = 2-7$ and $Re_\delta > 10^6$ [4-6]. Since the results of these references were obtained under different conditions, to allow comparison in terms of Re_δ number, the values of St_δ were reduced to a form that would exclude the influence of M_δ and $\bar{T}_w$ (Fig. 2a). When comparing these data with respect to temperature-ratio dependence we analogously excluded the influence of Reynolds and M_δ numbers (Fig. 2b).

Figure 2 also shows the results of our investigations — the solid lines calculated from Eq. (1), and also a broken line constructed from the empirical formula of [4]. It can be seen that the range of Re_δ and $\bar{T}_w$ in which heat transfer was investigated in our tests includes all the available test data, most of which were obtained for $Re_\delta < 10^7$ and $\bar{T}_w \approx 1$. The available test data agree quite well with the results of our tests, which indicates that we have expanded the range of investigation of local heat-transfer coefficients in the turbulent boundary layer to the large Reynolds number region ($\sim 10^8$) (Fig. 1a).

The results of our tests also agree satisfactorily with the results of calculating local heat-transfer coefficients obtained by the method of numerical integration of the boundary-layer equations of [7].

NOTATION

Re, Reynolds number; M, Mach number; $\bar{T}_w = T_w/T_r$, temperature ratio; T_w, model surface temperature; T_r, adiabatic surface temperature; T_δ, temperature at the outer edge of the boundary layer; St, Stanton number; α, heat-transfer coefficient; ρ, density; c_p, specific heat; v, velocity. The subscript δ denotes flow parameters at the outer edge of the boundary layer; $S = St_\delta \bar{T}_w^{0.24} (1 + 0.178\, M_\delta^2)^{0.47}$; $K = St_\delta Re_\delta^{0.18} (1 + 0.178\, M_\delta^2)^{0.47}$; $N = St_\delta Re_\delta^{0.18} \times \bar{T}_w^{0.24}$.

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