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HEAT EXCHANGE AT THE LATERAL SURFACE OF A BLUNT CONE DURING ABSORPTION OF THE ENTROPY LAYER BY THE LAMINAR AND TURBULENT BOUNDARY LAYER

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UDC 532.526-3.011.7

The entropy layer on a blunt body has a strong influence on flow in the boundary layer. In particular, allowance for absorption of the entropy layer leads to an increase in the heat flux [1-4]. The papers [1-3] are devoted to an investigation of this phenomenon in the laminar flow regime, while in [4] the influence of absorption of the entropy layer is analyzed for flow in the boundary layer with both a laminar and a turbulent character. This influence of absorption of the entropy layer on the heat flux is especially pronounced in a turbulent flow regime. It is advisable to make an experimental test of the calculated data of [1-4] by comparing the results of experiment and calculation for the same flow conditions. In the present paper such a comparison of experimental and calculated results, represented in similarity parameters, is made for the conditions of a shock tube at $M_\infty = 6.1$ and 8.

The shock tube operated on a pulsed scheme. The duration of the steady state of tube operation was ~ 0.02 sec. The model consisted of a spherically blunted circular cone with an aperture half-angle $\theta = 10°$ and a blunting radius $r = 3$ and 5 mm. The length of the model was 285.7 and 276.2 mm for $r = 3$ and 5 mm, respectively. For $M_\infty = 6.1$ the stagnation temperature was 564 and 730°K, the total pressure was varied in the range from $1.6 \cdot 10^6$ to $14 \cdot 10^6$ Pa, while the Reynolds number R_∞, calculated from the parameters of the undisturbed stream and the blunting radius, varied from $2.1 \cdot 10^4$ to $3.1 \cdot 10^5$. In the case of $M_\infty = 8$ the stagnation temperature was $T_0 = 737$°K, the total pressure was $9.5 \cdot 10^6$ and $14.5 \cdot 10^6$ Pa in the tests with $r = 3$ and 5 mm, respectively, and $R_\infty \simeq 1 \cdot 10^5$. The temperature factor t_w, expressed as the ratio of the enthalpy h_w of the surface of the cone to the stagnation enthalpy H_0 of the oncoming stream, was 0.40 and 0.52 for $T_0 = 730$ and 564°K.

On the test model we mounted 40 calorimetric converters (sensors) arranged along one generating line. The calorimetric converters were built in the form of a copper disk 2 mm in diameter. A microthermocouple was welded to the inner side of the disk in a point weld. Both its thermoelectrodes (Chromel and Copel) were rolled to a thickness of 0.03 mm and a width of 0.2 mm at the point of the weld. To install the converters* on the model we drilled openings 2.6 mm in diameter in its wall. A disk was fastened into an opening with epoxy

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*Converters of this type were developed by Yu. Yu. Kolochinskii, and the experiment in the tube was carried out with his participation.

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 5, pp. 65-69, September-October, 1985. Original article submitted July 4, 1984.

0021-8944/85/2605-0661$09.50

resin. The latter thermally insulates the converter from the metal wall of the model. The original thickness of the disks was 0.15 mm. After installation on the model, however, the disks were finished: Their projection above the surface of the cone was removed. As a result, the local projections of the converters on this surface do not exceed 5 μm. After the finishing, the disks had a thickness ranging from 0.10 to 0.15 mm.

Each converter, after installation on the model and finishing, was calibrated on a pulsed thermal calibration device (PTCD) [5]. A 32-channel amplifier [6] with light-beam oscillographs was used to record the signals of the converters.

To obtain the turbulent state of the boundary layer we used a turbulizer comprised of five rows of grains of emery powder 0.5 mm in size, which were arranged in checkerboard order with a spacing of 1 mm in each row and 2 mm between rows. The grains were fastened to the surface of the cone with epoxy resin. The first row of grains was set back at a distance x = 27 and 19 mm for r = 3 and 5 mm, respectively. To verify the efficiency of the turbulizer, we first tested a cone with a sharp apex, which we then blunted. The sharp cone was tested under the same tube conditions as the blunt cone. Reliable data exist for calculating the intensity of heat exchange on a sharp cone. Their comparison with the results of measurements on the model with a sharp apex showed that the turbulizer used is very efficient. The turbulent regime of flow in the boundary layer occurs at a distance of about 10 boundary-layer thicknesses downstream from the location of the last row of turbulizing elements.

The results of repeated measurements of the distribution of the local heat flux q along the generating line of a cone with r = 5 mm, using the turbulizer on the model, are presented in Fig. 1, where $c_h = q/[\rho_\infty u_\infty(H_0 - h_w)]$, ρ_∞ and u_∞ are the density and velocity of the undisturbed stream, and x is the distance along the surface of the cone, reckoned from the critical point. Here we also show the calculated distributions of c_h for the conditions under which the experiment in the shock tube was carried out. These distributions were obtained for a turbulent boundary layer, both with (solid lines) and without (dash–dot lines) allowance for absorption of the entropy layer. Allowance for absorption of the entropy layer considerably (by a maximum factor of 1.4) increases the values of c_h. The experimental results are in good agreement with those calculated functions obtained with allowance for absorption of the entropy layer. This important result indicates that the data of numerical calculations of boundary layers on blunt bodies without allowance for absorption of the entropy layer existing in the literature are not reliable.

In making the calculations we used a program of [7] for numerical integration of the equations of a two-dimensional boundary layer, modified so as to make it possible to calculate the stream parameters at the outer limit of the boundary layer with allowance for absorption of the entropy layer. These parameters are determined by equating the gas flow rate in each cross section of the boundary layer to the flow rate of gas passing through the section of the bow shock wave bounded by that streamlike reaching the outer limit of the boundary layer in the cross section under consideration (see [4]). The program enables one to calculate the boundary layer in laminar and turbulent regions of flow.

In the calculations it was assumed that the gas is ideal. The laminar Prandtl number was taken as 0.7 and the turbulent Prandtl number, as in the majority of work devoted to the calculation of a turbulent boundary layer, was taken as 0.9. Sutherland's formula was used for the dependence of the dynamic viscosity coefficient on temperature. The parameters of the inviscid flow were borrowed from [8].

Now let us turn to the derivation of the similarity parameters describing the phenomenon of absorption of the entropy layer by the turbulent boundary layer. For this we first estimate the characteristic length x along the surface of a blunt cone at which absorption occurs. Let the thickness of the entropy layer on the lateral surface of a blunt cone be δ_0 and let the characteristic gas density in the entropy layer be ρ_e. If we use the law of conservation of mass for flow in the entropy layer, then for δ_0 we obtain the estimate

$$\delta_0/r \approx (\rho_\infty/\rho_e)(u_\infty/u_e)(2k \sin\theta)^{-1},$$

where k = x/r is the dimensionless distance along the generating line of the cone; u_e is the characteristic velocity at the outer limit of the boundary layer. The thickness δ_x of the boundary layer is estimated using the expression

$$\delta_x \approx x/\mathrm{R}_e^{0,2}.$$

Here $Re = \rho_e u_e x/\mu_0$ (μ_0 is the viscosity coefficient at the stagnation temperature). Thus, we can obtain

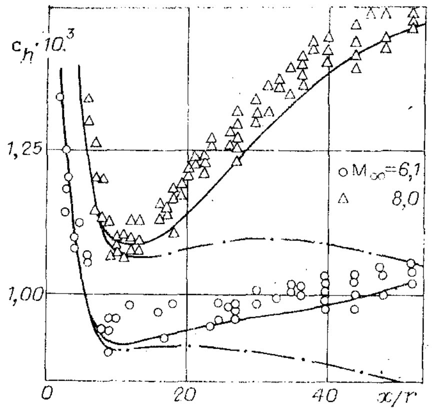

Fig. 1

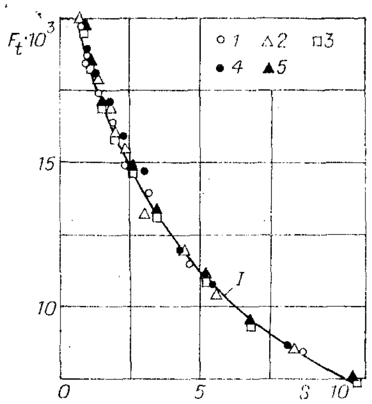

Fig. 2

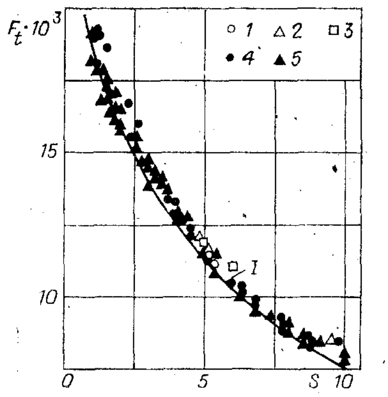

Fig. 3

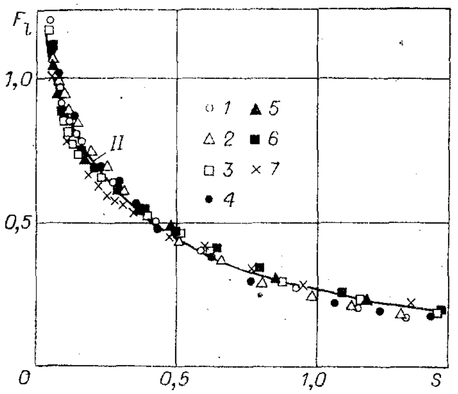

Fig. 4

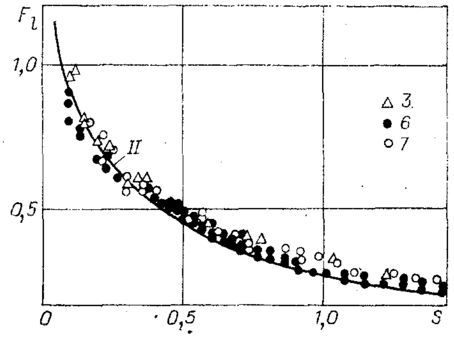

Fig. 5

$$\delta_x/r \approx k^{0,8}/(R_0 u_e/u_\infty)^{0,2},$$

where $R_0 = \rho_e u_\infty r/\mu_0$. In the case of the absorption of the entropy layer by the boundary layer, $\delta_x \approx \delta_0$, from which we have an estimate for the distance k at which absorption takes place:

$$k \approx R_0^{1/9}(\rho_\infty/\rho_e)^{5/9}(u_\infty/u_e)^{4/9}/(2\sin\theta)^{5/9}.$$

On the basis of this formula, we can choose a longitudinal coordinate S of order $O(1)$ to describe the phenomenon of absorption of the entropy layer by the turbulent boundary layer:

$$S = kR_0^{-1/9}(\rho_e/\rho_\infty)^{5/9}(u_e/u_\infty)^{4/9}(2\sin\theta)^{5/9}. \tag{1}$$

For a turbulent regime of flow in the boundary layer we write

$$c_H R_e^{0,2} = f,$$

where $c_H = q/[\rho_e u_e(H_0 - h_w)]$; $f = f(M_\infty, h_w/H_0, \theta, \ldots)$. If we introduce the longitudinal coordinate S into the expression for the number c_H, then we have the relation

$$F_t = c_H R_0^{2/9}(u_e/u_\infty)^{1/9}(\rho_\infty/\rho_e)^{1/9}(2\sin\theta)^{-1/9} = fS^{-0,2}. \tag{2}$$

We shall use the quantity $F_t(S)$ as the similarity parameter for heat transfer to the surface of a blunt cone in the regime of absorption of the entropy layer by the turbulent boundary layer.

For the case of absorption of the entropy layer by the laminar boundary layer, similar expressions were obtained in [3]:

$$S = kR_0^{-1/3}(u_e/u_\infty)^{1/3}(\rho_e/\rho_\infty)^{2/3}(2\sin\theta)^{2/3}; \tag{3}$$

$$F_l = c_H R_0^{2/3}(u_e/u_\infty)^{1/3}(\rho_\infty/\rho_e)^{1/3}(2\sin\theta)^{-1/3}. \tag{4}$$

The similarity parameters (1)-(4) for heat transfer in the regime of absorption of the entropy layer were used to treat experimental and calculated data obtained on the investigated cone in the range of S of from 0.5 to 10 and from 0.05 to 1.5 for turbulent and laminar boundary layers, respectively. The results are presented in Figs. 2 and 3 for the turbulent flow regime and in Figs. 4 and 5 for the laminar regime, with calculated results being given in Figs. 2 and 4 and experimental results in Figs. 3 and 5. The experimental and calculated points 1-7 correspond to M_∞ = 6.1, 6.1, 8, 6.1, 8, 6.1; R_∞ = $1.9\cdot10^5$, $2.7\cdot10^5$, $1.0\cdot10^5$, $3.1\cdot10^5$, $1.1\cdot10^5$, $3.5\cdot10^4$, $2.1\cdot10^4$; t_w = 0.52, 0.52, 0.40, 0.52, 0.40, 0.40, 0.40.

Points 4-6 are for r = 5 mm, while 1-3 and 7 are for r = 3 mm. In determining the similarity parameters S and F we took the values of u_e/u and ρ_e/ρ_∞ from the tabular data of [8].

In the investigated ranges of the parameters M_∞, R_∞, and t_w (M_∞ = 6-8, $R_\infty \leqslant 3.1\cdot10^5$, t_w = 0.40-0.52) the calculated results presented in Figs. 2 and 4 can be approximated by the relation $F^{-1} = a + bS$, where a = 44.88 and 0.8079 and b = 8.777 and 2.881 for turbulent and laminar (curves I and II) boundary layers, respectively. The proposed formula satisfactorily describes the measurement results (see Figs. 3 and 5). Thus the similarity parameters (1)-(4) enable one to treat experimental and calculated data with a small scatter of points.

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