CALCULATION OF HEAT TRANSFER IN SEPARATION ZONES WITH THE USE OF LOCAL FLOW PARAMETERS AT THE BOUNDARY OF THE WALL BOUNDARY LAYER

B. E. Luzhanskii, V. P. Solntsev,
and V. G. Limonov

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The results of an experimental investigation of heat transfer in turbulent separation zones before steps are presented. The experimental data are compared with the calculation on the basis of the relations used in the case of flow past a surface without separation and local flow parameters at the boundary of a wall boundary layer.

The purpose of this study was to check the possibility of calculating heat transfer in the wall boundary layer of turbulent separation zones before steps by methods of calculating heat transfer in the boundary layer with flow past a surface without separation.

The investigation was carried out at a subsonic velocity of the air flow. The experimental section represented a plate on which steps of various geometric shape were installed: two dimensional rectangular steps, three-dimensional steps in the form of cylinders with a diameter-to-height ratio of 2, and a rectangular parallelepiped with a width-to-height ratio of 1. Data obtained experimentally with plane steps of height H = 30 and 150 mm are presented in the article.

Two-dimensionality of the flow was provided by installing side walls of the channel. The absence of the influence of end effects on the flow and heat transfer in the greater part of the channel (excluding small sections near the side walls) was checked by special experiments. The steps and the plate were equipped in the plane of symmetry with packets of plane copper calorimeters from 1 to 5 mm wide and 0.5-mm-diameter drain holes. The heat fluxes were measured by the method of a regular regime of the first kind. The maximum total error of measuring the heat-transfer coefficient as a result of two measurements with probability 0.95 did not exceed 15%. The value of the temperature factor $T_{we} = 0.7$.

The flow in the separation zone was visualized by applying special colors on the surface of the step and plate. The local flow parameters at the boundary of the wall boundary layer in the separation zone were determined from the results of measuring the static pressure and the total pressure profiles in a number of sections near the surface of the step and plate. To measure the total pressure we used a microprobe with a plane receiving part of thickness 0.15 mm and width 2 mm. The results of determining the velocity at the boundary of the wall boundary layer based on the data of measuring the total and static pressures were checked (in certain sections) by measuring the velocity by means of an ÉTAM-3A hot-wire anemometer. The difference in the measurement results by other methods did not exceed 15%.

Figure 1 shows the results of treating the experimental data obtained in the accelerated flow sections from the spreading lines r and 2. It should be noted that the accelerated flow in section in the separation zone on the step amounts to 60% of the distance from point r to the base of the step and on the plate to 25-50% of the length of the separation zone. Here the maximum values of the heat fluxes on the plate are observed in the accelerated flow section.

The experimental data were treated in the following way. On the basis of the flow parameters at the boundary of the wall boundary layer and by the method in [1, 2] we calculated the effective coordinate x_e reckoned from the spreading lines r or 2. Then we determined the Nusselt number $Nu_e = \alpha x_e/\lambda_w$ and

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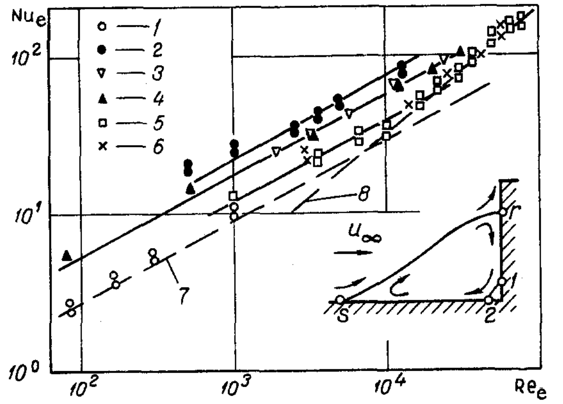

Fig. 1

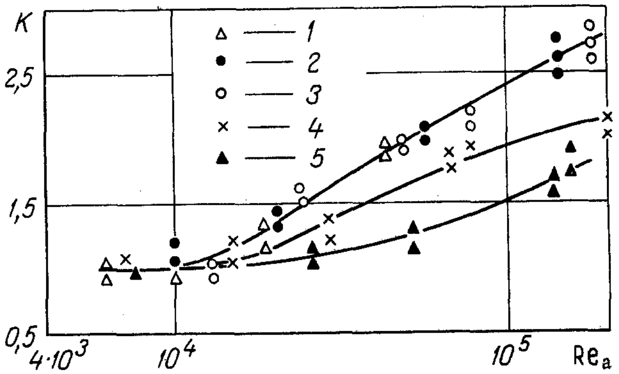

Fig. 2

Fig. 1. Data on heat transfer in the separation zone. For the step: 1) H = 30 mm, u_∞ = 41 m/sec, δ_s^* = 10 mm; 2) 30 mm, u_∞ = 340 m/sec, δ_s^* = 10 mm; 3) 30 mm, u_∞ = 340 m/sec, δ_s^* = 3 mm; 4) 150 mm, u_∞ = 122 m/sec. For the plate: 5) H = 30 mm, u_∞ = 340 m/sec, δ_s^* = 3 mm; 6) 150 mm, u_∞ = 122 m/sec; 7) according to relation (1); 8) according to relation (2)

Fig. 2. K vs Re_a for different values of δ_s^*/H (T_{we} = 0.7): 1) δ_s^*/H = 0.8; 2) 0.38; 3) 0.15; 4) 0.1; 5) 0.03.

Reynolds number $\mathrm{Re}_e = \rho_w u x_e/\mu_w$. The relations $\mathrm{Nu}_e = f(\mathrm{Re}_e)$ obtained were compared with the relations for calculating heat transfer on a plate in the case of laminar and turbulent boundary layers:

$$\mathrm{Nu} = 0.332\,\mathrm{Re}^{0.5}\left(\frac{\mu_\infty\rho_\infty}{\mu_w\rho_w}\right)^{0.44}\sqrt[3]{\mathrm{Pr}} \tag{1}$$

and

$$\mathrm{Nu} = 0.029\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4}\,T_{we}^{0.39}. \tag{2}$$

We will consider the data on heat transfer in the accelerated flow section on the step. In the vicinity of the spreading line r there is a unique laminar regime of heat transfer described by the relation

$$\mathrm{Nu}_e = A\,\mathrm{Re}_e^{0.5}. \tag{3}$$

For small flow velocities and heights of the step (Fig. 1, 1) the experimental data are close to the dimensionless relation (1) for calculating heat transfer in a laminar boundary layer on a plate. With an increase of flow velocity (2) the relation $\mathrm{Nu}_e \sim \mathrm{Re}_e^{0.5}$ is retained, but we observe stratification of the data corresponding to an increase of the proportionality factor A. The proportionality factor A depends also on the linear dimensions of the separation zone, for example, an increase of the height of the separation zone h_r (distance from the base of the step to point r) from 19 to 69 mm resulted in a value of A ≈ 0.6 being obtained at velocity u_∞ = 122 m/sec (Fig. 1, 4) instead of u_∞ = 340 m/sec (3). In addition, a change of δ_s leads to stratification of the experimental data and to a change of A, which is seen from a comparison of 2 and 3.

The effect of increased turbulence in the separation zone on heat transfer in the laminar flow sections in the wall boundary layer may be a possible cause of intensification of heat transfer and increase of A by a factor of 2-3.

The measurements by the ÉTAM-3A hot-wire anemometer showed that the intensity of turbulence at the boundary of the wall layer in the two-dimensional separation zone reached 20-60% depending on the parameter δ_s^*/H and prehistory of the flow.

Intensification of heat transfer in the separation zone can be characterized by the coefficient K

$$K = \frac{\mathrm{Nu}_e}{0.332\,\mathrm{Re}_e^{0.5}\left(\frac{\mu_\infty\rho_\infty}{\mu_w\rho_w}\right)^{0.44}\sqrt[3]{\mathrm{Pr}}}. \tag{4}$$

The change of K in the accelerated flow section on the two-dimensional rectangular step is shown in Fig. 2. An analysis showed that K depends on δ_s^*/H and on the Reynolds number $\mathrm{Re}_a = \rho_w u_a h_r/\mu_w$, where u_a is the maximum velocity at the boundary of the wall boundary layer on the step. It is interesting to note that when $\mathrm{Re}_a < 10^4$ intensification of heat transfer does not occur and K = 1 in the entire investigated range of δ_s^*/H. For large Re_a number a decrease of δ_s^*/H corresponding to the decrease of turbulence intensity leads to a decrease of K. Thus, a change of $K = f(\mathrm{Re}_a, \delta_s^*/H)$ agrees qualitatively with the data in [3] on the effect of the Reynolds number and turbulence intensity of the external flow on heat transfer in a laminar boundary layer in a flow with a positive velocity gradient.

Similar results were obtained on investigating heat transfer in the accelerated flow section in the separation zone on a plate (before two-dimensional steps). For large Reynolds numbers the laminar regime of heat transfer is retained only in the immediate vicinity of the spreading line 2, and then comes a section with a turbulent regime. We see from Fig. 1 that 5 and 6 for large Reynolds numbers coincide with relation (2) for a turbulent boundary layer.

Thus heat transfer in accelerated flow sections in separation zones can be determined from the relations obtained for flow without separation and from the local flow parameters at the boundary of a wall boundary layer. However, here it is necessary to take into account intensification of heat transfer in laminar flow sections in the wall boundary layer of turbulent separation zones.

NOTATION

H	is the height of step;
h_r	is the height of separation zone;
x_e	is the effective coordinate reckoned from the spreading line;
δ_s^*	is the displacement thickness of boundary layer at separation line;
u_∞	is the velocity of oncoming flow;
u, u_a	are the velocities at boundary of wall boundary layer and maximum velocity at boundary of wall layer of step;
ρ	is the density;
μ	is the dynamic viscosity coefficient;
λ	is the thermal conductivity;
α	is the heat-transfer coefficient;
T_{we}	is the temperature factor;
Pr	is the Prandtl number;
$\mathrm{Nu}_e = \alpha x_e/\lambda_w$	is the Nusselt number;
$\mathrm{Re}_e = u x_e \rho_w/\mu_w$ and $\mathrm{Re}_a = u_a h_r \rho_w/\mu_w$	are the Reynolds number.

Subscripts

∞,	refers to the parameters of oncoming flow;
w,	refers to on the surface.

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