EXPERIMENTAL INVESTIGATION OF THE HEAT EXCHANGE IN SEPARATION ZONES OF A TURBULENT BOUNDARY LAYER AHEAD OF A STEP

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Results of an experimental investigation of the heat exchange in separation zones of a two-dimensional turbulent boundary layer ahead of a rectangular step are elucidated for a subsonic air stream velocity.

The investigation was carried out for a 0.09-4 change in the ratio between the boundary layer thickness in the separation section and the height of the step, a $1.7 \cdot 10^4$-$4.2 \cdot 10^5$ Reynolds number computed by means of the stream parameters and the step height, and a 1.1-200 Euler criterion. The temperature factor was 0.7. A brief description is given of the experimental setup and of the methodology of the experiments.

It is shown that the distribution of the heat transfer coefficients in the separation zone is not self-similar and depends on the flow diagram, the Reynolds and Euler numbers, and the relative thickness of boundary layer displacement at the line of separation.

Criterial dependences which generalize the data on heat exchange at characteristic points of the separation zone and dimensionless distributions of the heat transfer coefficients, which permit an engineering computation of the heat exchange at a step and on a plate, are obtained.

Also presented are results of investigating the flow diagrams, the characteristic dimensions of the separation zones, and the static pressure distributions needed to compute the heat exchange.

The flow diagram ahead of the step is shown in Fig. 1.

NOTATION

x, h – distance on the plate and step, measured from the base of the step; H – height of the step; u – velocity; ρ – density; p – static pressure; μ – coefficient of dynamic viscosity; λ – coefficient of heat conductivity; α – coefficient of heat transfer; α_0 – coefficient of heat transfer on a plate without a step; σ – Prandtl criterion; δ, δ^*, ϑ – dimensionless thickness, displacement thickness, and thickness of the loss of boundary layer momentum in the separation section referred to the step height H.

$$x^\circ = \frac{x}{H}, \quad h^\circ = \frac{h}{H}, \quad h' = \frac{h}{h_2}, \quad h^* = \frac{h - h_2}{H - h_2}$$

$$\alpha^\circ = \frac{\alpha}{\alpha_0}, \quad \alpha' = \frac{\alpha}{\alpha_2}$$

$$C = \frac{2(p - p_0)}{\rho_0 u_0^2}, \quad E = \frac{p_0}{\rho_0 u_0^2}; \quad R_0 = \frac{u_0 \rho_0 H}{\mu_0}$$

SUBSCRIPTS

0 – free stream parameters; 1, 2, 5 – parameters at appropriate separation and attachment points.

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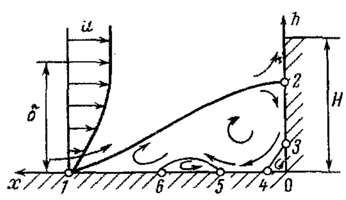

Fig. 1

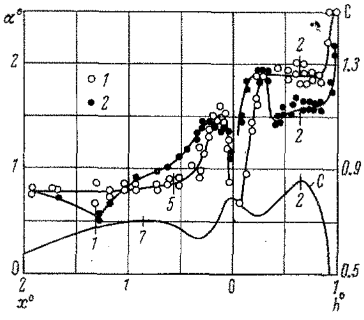

Fig. 2

TABLE 1

R_*	$E = 1.5$	3	60	140
$3.3 \cdot 10^3$	—	—	—	1.3*
$5 \cdot 10^3$	—	—	0.7*	0.7
$9 \cdot 10^3$	—	1*	0.9	1.2
$1.5 \cdot 10^4$	1.1*	1	1.1	
$2 \cdot 10^4$	1.1	1.1	1.2*	
$7 \cdot 10^4$	1.5	1.6*	—	
$1.1 \cdot 10^5$	1.7*	—	—	

1. The experiments were conducted in a subsonic wind tunnel with open working section whose description is presented in [1]. The Mach number reached 0.85, the number $R_0 = 1.7 \cdot 10^4 - 4.2 \cdot 10^5$, the magnitude of the temperature factor is $T_{W0} = 0.7$.

The experimental section was a 260- or 80-mm-wide rectangular channel open at the top, with an 8- to 45-mm-high step mounted on its bottom. The two dimensionality of the flow was assured by the presence of side walls from which the boundary layer poured through a slot in front of the separation zone. Checking experiments with a variable channel width showed the absence of the influence of tip effects on the flow and the heat exchange over the measurement section before the step. The construction of the experimental section assured a change in the thickness of the turbulent boundary layer on the line of separation from 2.7–34 mm before the step, from 1.6–3 in the form parameter, and from 0.09–4 in δ.

The heat exchange was investigated by a method based on the theory of a regular regime of the first kind. Packets of 31 and 20 flat, 1-5 mm thick, copper calorimeters were disposed in the plane of symmetry of the plate and step. The change in calorimeter temperature was determined on OT-24 oscillographs. An analysis in the measurement errors and the processing of the results of several checking experiments showed that the ultimate total error of the final result of a single measurement of the heat transfer coefficient did not exceed 20% with the probability 0.95. To diminish the total error of the final result of the measurements, from two to four measurements of α were made in each regime.

2. Data characterizing the flow in the separation zone are necessary for an analysis and generalization of the heat exchange data in the complex flow domain ahead of the step. Hence, besides the measurements of the local heat transfer coefficients, the flow picture was investigated by using flow visualization on the model surface. Characteristic dimensions of the separation zone, the static pressure distribution on the step and plate surface, as well as the boundary layer parameters in the separation section were determined.

Two flow diagrams in the separation zone with boundary layer separation at point 1 and attachment at point 2 (Fig. 1), which are distinctive by the presence of additional circulation zones, were hence developed.

Type A Flow. One additional circulation zone, formed as a result of boundary layer separation at the point 3 near the wall and its attachment at the point 4 on the plate, is observed in the separation zone.

Type B Flow. Besides the zones 3-4 there exists still another additional circulation zone with boundary layer separation near the wall at the point 5 and attachment at the point 6.

Let us present average dimensionless coordinates of points 1 and 2 for some values of δ^*:

$\delta^* =$	0.03	0.06	0.1	0.4	0.8	1.2
$x_1^\circ =$	0.7	1.2	1.3	1.32	1.1	0.9
$h_2^\circ =$	0.38	0.6	0.65	0.65	0.65	0.65

Presented in Table 1 are data on the magnitude of the dimensionless coordinate of the line of boundary layer separation near the wall x_5/h_2. The boundary of the domain of existence of diagrams of A and B flows can also be determined from the data in the table. The limit values of the numbers R_* for which a type B flow is still realized for a given value of the criterion E are marked with an asterisk in the table. The flow in the separation zone outside the mentioned boundaries is of type A. The number R_* is computed by means of the dependence

$$R_* = \frac{u_0 h_2 \rho_*}{\mu_0} \left[(C_2 - C_*) \frac{\rho_0}{\rho_*} \right]^{0.5} \tag{2.1}$$

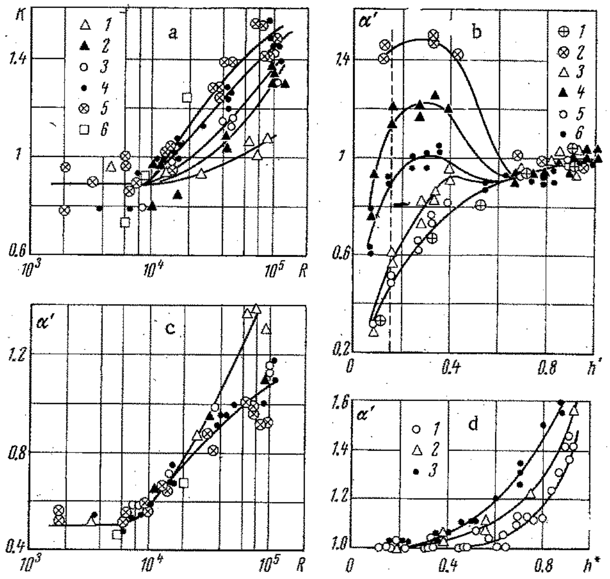

Fig. 3

The asterisk denotes parameters for a characteristic pressure in the separation zone on the plate (at point 7 in Fig. 2).

The dependences

$$C_* = 0.37\,(\delta^*)^{-0.25}, \quad C_2 = 0.43\,(\delta^*)^{-0.25} \tag{2.2}$$

were obtained as a result of investigating the static pressure distribution in ranges of variation of δ^* from 0.028-1.5 and of δ^*/ϑ from 1.6-3.

The last dependence is valid for $\delta^* = 0.033\text{-}1.5$. Upon the diminution of $\delta^* < 0.033$ the value of C_2 approaches unity asymptotically. Moreover, a dependence extending the static pressure distribution on a plate up to the separation zone has been obtained:

$$\frac{C}{C_*} = 1 - \exp\{-3.5\,[(x^\circ - x_1^\circ)\,(\delta^*)^{-0.1} + 1]^{-1}\} \tag{2.3}$$

3. Presented in Fig. 2 are typical distributions of the heat transfer coefficients in the separation zone. Local values of α are referred to the appropriate experimental values of the heat transfer coefficients on a plate without a step α_0.

The values of α on the step have been referred to the value of α_0 at a point coincident with the base of the step. The experimental results corresponding to the point 1 have been obtained for the values $\delta^* = 0.1$, $T_{W0} = 0.7$, $R_0 = 3.5 \cdot 10^4$, and $E = 80$. Values of α corresponding to the point 2 have been obtained for the same values of δ^* and T_{W0}, but for $R_0 = 2.9 \cdot 10^5$ and $E = 1.1$. The distribution of the static pressure coefficients is also presented for the second regime in Fig. 2, and the coordinates of the boundary layer separation and attachment points are shown. An analysis of the experimental results showed that the distribution of the heat transfer coefficients in the separation zone is not self-similar but depends on the numbers R_0, E, and δ^*.

Let us examine the heat exchange on the step surface. Data on the static pressure distribution on the step surface, the total pressure, and velocity on the boundary of the boundary layer near the wall permitted making the conclusion that the relationship

$$\left(\frac{du}{dh}\right)_2 \sim \frac{u_*}{h_2} = \frac{u_0}{h_2}\left[(C_2 - C_*)\frac{\rho_0}{\rho_*}\right]^{0.5} \tag{3.1}$$

where u_* is the velocity on the separating streamline in the separation zone, can be used for an approximate estimation of the magnitude of the velocity gradient at the point 2 in the whole range of numbers R_0, E, and δ^* investigated.

Assuming the heat exchange at the point 2 to depend on the velocity gradient analogously to the heat exchange on the line of spreading of a two-dimensional laminar boundary layer, the computation of α_2 can be carried out by means of the criterial dependence

$$N = KR^{0.5} \qquad \left(N = \frac{\alpha_2 h_2}{\lambda_2},\ R = \frac{u_* h_2 \rho_2}{\mu_0}\right) \tag{3.2}$$

Presented in Fig. 3 are experimental results on the magnitude of the proportionality coefficient K obtained for the values $T_{W0} = 0.7$ and $\sigma = 0.7$. The experimental points 1, 2, 3, 4, 5, and 6 correspond to values of δ^* equal to 0.03, 0.06, 0.1, 0.2, 0.5, and 0.8. The dependence of the coefficient K on R and δ^* is possibly explained by the influence of turbulence on heat exchange in a laminar boundary layer. Measurements made using an ÉTAM-3A thermoanemometer showed that the intensity of turbulence in the neighborhood of point 2 reached 20-60%, where an increase in δ^* resulted in a growth in intensity of turbulence in the separation zone.

The results on the change in $K = f(R, \delta^*)$ agree qualitatively with results in [2] on the influence of the intensity of stream turbulence and Reynolds number on the intensification of heat exchange in a laminar boundary layer. Exactly as in the paper mentioned, there is a limit value of the Reynolds number $R = 10^4$ in this case before which the hypothesized influence of turbulence is not manifest and the coefficient K is independent of R and δ^*.

Shown in Fig. 3b is the dimensionless heat flux distribution in the separation zone on the step. Local values of the heat transfer coefficients are referred to values of α_2. The experimental points 1, 3, 5 have been obtained for $R_0 = 3.5 \cdot 10^4$, at points 2, 4, 6 for $R_0 = 2.9 \cdot 10^5$. Values of the parameters δ^* for points 1 and 2, 3 and 4, 5 and 6, respectively, equal 0.03, 0.1, and 0.33. The distribution of α' is not self-similar and depends essentially on the numbers R_0 and δ^*. For small R_0 (points 1, 5) the heat fluxes diminish from point 2 to the base of the step. An increase in R_0 results in the appearance of a heat flux maximum on the step (points 2, 4, 6). An analogous change in the nature of the heat flux distribution on the step also causes a change in the parameter δ^* resulting in an increase in the local Reynolds numbers on the step.

Analysis of the heat exchange and local flow parameters results showed that the regime of heat exchange and flow in the boundary layer near the wall can be laminar, transitional, and turbulent. The appearance of transitional and turbulent portions of the flow results in an abrupt increase in the heat fluxes, which explains the difference in the nature of the distribution of α on the step surface. Lamination of the curves in Fig. 3b does not occur in the absence of portions with transitional and turbulent regimes.

Examination of the results on the magnitude of α' for a fixed value of the coordinate $h' = 0.15$ (Fig. 3c), as well as analogous dependences obtained for other fixed values of h', shows that for $R < 6 \cdot 10^3$ the distribution $\alpha' = f(h')$ in the separation zone on a step is independent of R_0, E, and the parameter δ^*. (The notation in Fig. 3c agrees with the notation in Fig. 3a.)

Data on the quantity α' for $h' = 0.15$ can be used to find the distribution of α in the separation zone on the step. The distribution $\alpha' = f(h')$ is hence determined by means of the average curve in Fig. 3b which passes through a point with abscissa $h' = 0.15$ and ordinate corresponding to the value of α' determined by means of the results in Fig. 3c. The dimensionless distribution of heat transfer coefficients on the step outside the separation zone in the range of parameters investigated is independent of R_0 and E and may be determined from the data in Fig. 3d. The experimental points 1, 2, and 3 correspond to values of δ^* equal to 0.1, 0.2, and 0.5.

Let us consider the heat flux distribution on a plate (see Fig. 2). The character of the distribution of α on the plate depends on the flow diagram in the separation zone. For a flow diagram A (point 2), α does not vary from the maximum which is found in the accelerated portion of the flow from the point 4 to the minimum at the point of separation 1. For a flow diagram B, to which the experimental points 1 in Fig. 2 correspond, the fundamental diminution in α occurs before the point of separation 5, and the change in α is insignificant in the 5-1 portion of the flow.

Results on the maximum value of the heat transfer coefficients on the plate ahead of the step α_m are shown in Fig. 4 for the values $T_{W0} = 0.7$ and $\sigma = 0.7$. The experimental points 1, 2, 3, 4, and 5 have been obtained for 0.06, 0.1, 0.2, 0.5, and 0.8 values of δ^*, respectively. The results of experiments in the whole range of investigated R_0, E and of the parameter $\delta^* = 0.06$-0.08 are generalized satisfactorily by the one criterial dependence

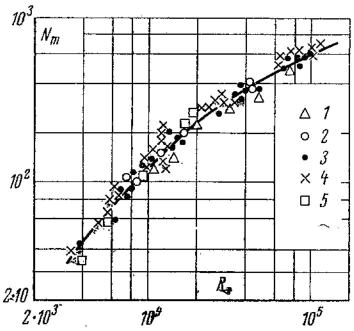

Fig. 4

$$N_m = \frac{\alpha_m h_2}{\lambda_0} = f(R_*)$$

which is shown as a curve in Fig. 4.

Processing the experimental results showed that the heat transfer coefficient at the point of separation α_1 can be calculated by the method proposed in [3]. Using this method yields good results in computing the heat exchange ahead of the separation zone up to the line of separation inclusive, in the whole range of δ^* investigated.

The dimensionless distribution of the heat transfer coefficients in the separation zone on a plate in the form

$$\alpha^* = \frac{\alpha - \alpha_1}{\alpha_m - \alpha_1} = f(x^*)$$

is presented in Fig. 5, where x* is a characteristic dimension.

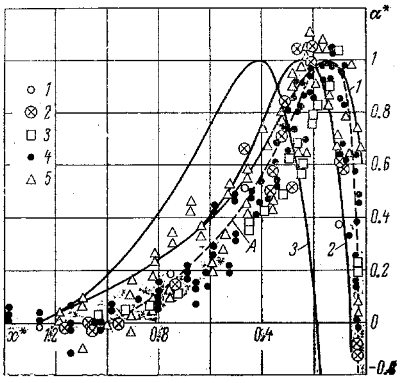

Fig. 5

For an A type flow in the separation zone $x^* = x/x_1$, while $x^* = x/x_5$ for a B type flow. The experimental points 1, 2, 3, 4, and 5 in Fig. 5 refer to A type flow and correspond to $R_0 \cdot 10^{-5}$ equal to 0.4, 0.7, 1.1, 3, and 8.5. All the results for $R_0 > 2 \cdot 10^4$ and $\delta^* = 0.06$–0.8 can be generalized by one dependence shown by the dashed curve A.

Dimensionless distributions of the heat transfer coefficients for B type flow are shown by the solid lines 1-3 in Fig. 5. In this case the α^* distribution is not self-similar, which is associated mainly with the significant change in the coordinate x_5 as a function of the numbers R_* and E for an insignificant change in the position of the maximum α on the plate. The coordinate of the maximum α is approximately $0.3h_2$ in the range of parameters investigated; hence, the ratio x_5/h_2 can be used as a parameter governing the lamination of the dimensionless curves. The values $x_5/h_2 = 1.7$, 1, and 0.7 correspond to curves 1, 2, and 3 in Fig. 5.

4. As a result of the work carried out, the heat exchange in the separation zone of a turbulent boundary layer in front of a step has been investigated in a range of variation of the relative boundary layer thickness on the line of separation between 0.09 and 4, of the boundary layer form factor δ^*/ϑ from 1.6 to 3, of the Reynolds number $R_0 = 1.7 \cdot 10^4$–$4.2 \cdot 10^5$, and the Euler criterion E = 1.1-200.

It is shown that the distribution of the heat transfer coefficients in the separation zone is not self-similar and depends on the flow diagram, the values of the Reynolds and Euler criteria, the relative thickness of boundary layer displacement on the line of separation.

Criterial dependences which generalize heat exchange data at the characteristic points of the separation zone, and dimensionless distributions of the heat transfer coefficients, permitting an engineering computation of the heat exchange on the surface of a step and a plate, have been obtained.

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