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INTEGRAL CHARACTERISTICS OF THE BOUNDARY LAYER IN RELAXATION ZONE AFTER A LOCAL CLOSED SEPARATION

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The results of the experimental study of the integral characteristics (friction and heat transfer coefficients, profiles of velocity and temperature, characteristic thicknesses and shape parameters) are presented for the relaxating flow downstream of a separation of various types in case of low free stream turbulence $Tu_e \approx$ *0.2 % and velocities of an external flow* $U_e \approx$ *5 - 10 m/s. The type of a separation (laminar, transitional or turbulent) is adjusted by the shape of an inlet edge of the plate and the length of an intercepter, installed in the test section of the wind tunnel. The measurements confirm extremely slow recovery to a "classical" turbulent boundary layer after various types of a separation. They also demonstrate the dissimilarity of an internal structure and different rates of recovery in hydrodynamic and thermal boundary layers in relaxation zone both in an inner region and at an outer part of ones.*

Keywords: boundary layer, relaxating flow, relaxation zone, turbulence, heat transfer, turbulent viscosity.

INTRODUCTION

For many years due to wide spread in industrial and environmental engineering the great attention has been paid to transport processes in a boundary layer developing in the presence of a closed local separation. Extensive studies were devoted to the separation itself and the recovering flows downstream of the separation region [1-11].

Despite numerous attempts to penetrate into the mechanism of a separation and distortions caused by it in an internal structure of a dynamic and thermal boundary layer in zones of reattachment and relaxation, many aspects of these complex flows remain unknown and unpredictable. Thus there are no reliable recommendations for determination of reattachment length and height; there are absent the universal criteria for estimation of the separation intensity; there are limited data on transformation of velocity and temperature turbulence in relaxation zone, etc.

Most the experiments and calculations were made for momentum transport. The problems connected with the influence of a separation on heat transfer remain obscure. Generally the number of experimental investigations on hydrodynamics substantially exceeds those on heat transfer, numerical simulation predominating over the experiments. Questions, concerning the memory (or relaxation) after a closed separation, are not widely studied especially in the important case when surface heat transfer occurs.

Thus far it is not clear: how can the typical dimensions of the relaxation zone be defined and predicted; how does the highly distorted turbulence around reattachment reorganize itself towards the more usual boundary layer forms; how can the intensity of a separation in terms of subsequent effects on the developing after it a boundary layer be characterized; how can the type of a separation (laminar, transitional or turbulent) be diagnosed, etc.? The lack of the experimental information restricts the possibilities of calculation methods as well as an extension of new phenomenological approaches for description of main features of a separation itself and relaxation zone after it.

That is why for many years in IET NASU the experimental investigations of heat transfer and hydrodynamics have been carried out for separated flows [7, 8, 10, 12, etc.]. The experiments presented here are specially designed for the flow downstream of reattachment rather than the separation region itself. The experimental arrangements are described in the following section and subsequent sections contain some of the results.

It is necessary to note that the presented results do not pretend to universal correlations or generalization. Their goal is to emphasize the common problems of the relaxating flow in the process of its very slow recovery to a ”classical” turbulent boundary layer after a separation of different type. Some aspects of studied problem are discussed below.

EXPERIMENTAL ARRANGEMENT

The experiments were conducted in the typical low-velocity open type wind tunnel T-5 IET NASU with a test section of 120x120x800 mm (Figure 1). The confuser (designed by Lespinar’s curve with contraction 9) ensured the smooth passage to the test section. Damping chamber had 5 identical sections with deturbulizing grids and filters.

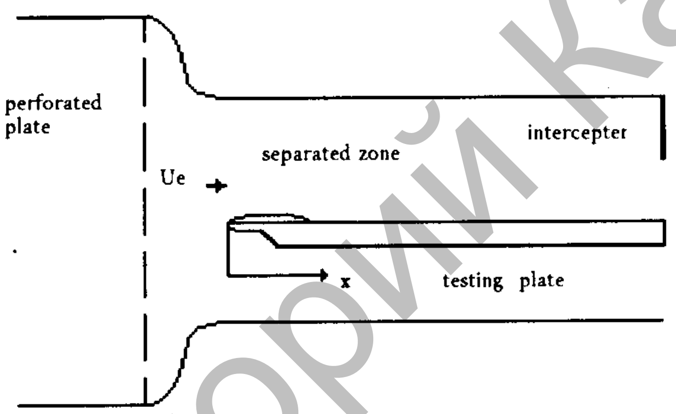

Fig. 1 Sketch of the experimental arrangement

The level of flow turbulence was varied by 10 mm thick perforated plates (PP) with perforation diameter 13.5 mm placed at the inlet to the wind tunnel confuser. The experiments, the results of which are presented below, were specially carried out without turbulence generator (PP0). In this case the natural turbulence level in the initial section of the tunnel was about 0.2% and a “pure” separation of different type and intensity ”worked” as a generator of turbulence in a boundary layer.

The intensity of a separation was adjusted by following methods:

1. by the values of mean velocity of an external flow ($U_e \approx$ 5 - 10 m/s);
2. by the height of an interceptor located in the end of test section on its top wall;
3. by the shape and thickness of the plate inlet edge.

The changes of height of an interceptor caused the essential redistribution of pressure near the inlet edge; however the streamwise pressure gradient along the rest of the plate part was practically absent. Thus there were realized flows without and with a separation of different types and intensity near the inlet edge of the plate.

In the experiments designated as PP0-0, PP0-25 and PP0-60 the latter figures corresponded to the height of the interceptor in mm.

The plate under study, the leading edge of which was rounded off by a radius of 1.5 mm (2h=3 mm) or was blunt (2h=7.5 mm), was installed in the tunnel test section at height of 20 mm above its bottom wall, i.e. the upper (working) and low surfaces of the plate were streamlined asymmetrically.

The main plate part of thickness of 10 mm and length of 770 mm was made of cloth-based laminate (textolite). Heat transfer was explored by electrocalorimetry, using six surface ribbon-type heaters with individual power control, glued along the plate. The inlet plate part of the length of 30mm was made from brass. Additional heating of the inlet part provided simultaneous development of thermal and dynamic boundary layers. Due to the combination of the electrocalorimetrical method on the main part of the plate with additional heating of its inlet part, the boundary conditions were approximately $t_w \approx$ const and $q_w \approx$ const at x<30 mm and x>30 mm respectively.

Parameters of velocity and temperature turbulence were measured by the DISA-55M hot-wire system with 1μ and 5μ probes; coefficients of friction were determined by modified Clauser's method in turbulent boundary layer (k=0.4 and C=5.1) or on the basis of velocity profiles. The length of the reattachment region was determined by method developed in IET NASU and based on changing thermoanemometer signal in this region.

The research program consists of three stages:

1. The first stage involved an experimental study of local values of friction and heat transfer coefficients, velocity and temperature profiles, their characteristic thicknesses and shape parameters. The results of this stage are presented in given paper.
2. On the second stage the main attention was paid to distributions of velocity and temperature fluctuations and their spectral composition.
3. The third stage was devoted to development of common approach for calculation of heat transfer using turbulent viscosity at the outer edge of a boundary layer.

The results of stages 2 and 3 will be presented in the next paper.

THE TYPES OF SEPARATION

Characteristics of five cases under study are given in the Table. As seen from the Table, the following types of a separation were observed in experiments: turbulent of various intensity (cases 4 and 5), transitional (case 3) and laminar (case 2). In case 1 the separation was absent.

Table.

Case	1	2	3	4	5
Des.	**PP0-60**	**PP0-25**	**PP0-25**	**PP0-0**	**PP0-0**
Inlet edge, mm	rounded 2h=3	rounded 2h=3	rounded 2h=3	rounded 2h=3	blunt 2h=7.5
U_e, m/s	10	5	10	10	10
x_r, mm	-	25	10	10	30
Type of separation	without separation	laminar	trans.	turbulent	turbulent
Symbols: dynamic thermal	□ -	+ -	○ ●	Δ ▲	× -

For diagnostics of the types of separation the distributions of mean in time velocities were used after reattachment point at x=50 mm. The values of turbulent viscosity at an outer edge of the dynamic boundary layer confirmed the chosen type of separation. The problems connected with determination of turbulent viscosity at an outer edge of a dynamic boundary layer will be discussed in the next paper.

COEFFICIENTS OF FRICTION AND HEAT TRANSFER

Before the description of the experimental results we would remind the following circumstances. We have no a goal to obtain the universal recommendations for calculation of intensity of transport processes (friction or heat transfer) or universal correlations and criteria in the relaxation zone after a separation of different nature. Our main goal is to present experimental, to some extent, inconclusive data about variations of the most important characteristics of the dynamic and thermal boundary layer first of all for zone of "slow" relaxation. Due to approximate estimation, in case of a turbulent separation the beginning of this zone corresponds ~$3.3\,x_r$, whereas the end is not known because it has not been achieved in any investigation, devoted to characteristics of relaxation zone. To some extent it is connected with such "curious" fact that the outer flow recovers substantially slower than the inner one [11] and a separation manifests itself as a generator of an external turbulence [7, 10]. We did not attempt to use the dimensionless parameters involving the length of reattachment taking into account uncertainty of its determination [10].

Generalizing the experimental data on transport processes in zone of relaxation after a separation, the current coordinate ($x - x_r$) is usually used as a determining geometrical size. As it was shown in [10], it is correct only for turbulent separation at reasonably high Reynolds numbers, when $x_r / h \approx \mathrm{const}$, i.e. at $\mathrm{Re}_h \geq 10^4$. In given experiments the x_r / h values changed nonmonotonously (see the Table). Therefore Reynolds number Re^{**} based on a momentum thickness was chosen to present data on friction and heat transfer. In our opinion this choice is rather successful because as it will be shown below local Reynolds number Re^{**} quite satisfactorily correlates the integral changes in structure of the dynamic and thermal boundary layers, caused by a separation.

Variations of local coefficients of friction and heat transfer are presented in Figures 2 and 3. To compare with a "classical" boundary layer the following dependencies were used [13, 14]:

for laminar boundary layer:

$$C_{f0} = 0.44\,\mathrm{Re}^{**-1}, \qquad (1)$$

$$St_0 = 0.365\,\mathrm{Re}^{**-1}; \qquad (2)$$

for turbulent boundary layer:

$$C_{f0} = 0.027[1 + 0.05(\lg \mathrm{Re}^{**} - 3.3) + 0.1(\lg \mathrm{Re}^{**} - 3.3)^2]\,\mathrm{Re}^{**-0.268}, \qquad (3)$$

$$St_0 = 0.0144\,\mathrm{Re}^{**-0.25}. \qquad (4)$$

The equation (3) was recommended in [13] taking into account the influence of low Reynolds numbers on the wake parameter values.

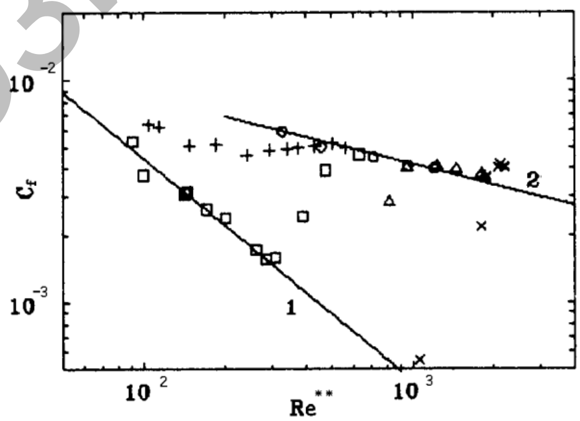

Fig. 2 Friction coefficients versus Re^{**}. 1-eq. (1); 2-eq. (3)

As seen from Figures 2 and 3 when a separation is absent a typical laminar-turbulent transition takes place (case 1, PP0-60). After a laminar boundary layer, characterized by the decrease of coefficients of friction and heat transfer, the latter substantially increase in the region of transition with further declining in a turbulent boundary layer. The points of the start (Re^{**}_{st}) and end (Re^{**}_{end}) of a dynamic and thermal transition practically coincide, the length of transition (estimated as usual by relation of $Re^{**}_{end} / Re^{**}_{st}$) being ~ 2.6. These data agree with the known features of laminar-turbulent transition described for example in [15].

Cases 2 and 3 are identical from the point of view of their geometry (PP0-25) but differ by velocities ($U_e \approx 5$ and 10 m/s).

In case 2 after a laminar separation the pseudolaminar boundary layer develops and transforms into the quasiturbulent boundary layer through the bypass transition. The distributions of friction coefficients along the plate $C_f = f(Re^{**})$ are nonmonotonous which is one of the main indications of any transition, whereas the distributions of heat transfer coefficients exhibit an obvious tendency to disappearance of nonmonotonicity of the variation $St = f(Re^{**})$.

As the result of the appearance of the pseudolaminar or quasiturbulent boundary layer the bypass transition can start and end at higher C_f and St values than those in initial “classical” laminar or turbulent boundary layer.

In case 3 after a transitional separation the bypass transition begins immediately without a stage of a pseudolaminar boundary layer. The variations of coefficients of friction and heat transfer become monotonous despite the presence of bypass transition, after which the quasiturbulent boundary layer follows.

Such unusual forms of bypass transition were first observed in [16] and named “upper”. In our opinion the origin of “upper” bypass transition in a boundary layer owing only to the presence of a laminar or transitional separation at comparatively low free stream turbulence is an important fact for engineering. It is obvious that it is impossible to predict the influence of a separation type on the development of boundary layers and intensity of transport processes in zone of relaxation without special experiments using even the very modern theories and turbulence models.

In cases 4 and 5 (PP0-0) at $U_e \approx 10$ m/s after a turbulent separation in zone of “fast” relaxation ($x / x_r < 3.3$) the global growth of friction coefficients takes place whereas the heat transfer coefficients decline remaining substantially higher than in “classical” turbulent boundary layer. In zone of “slow” relaxation the very long quasiturbulent boundary layer develops along the rest part of the plate.

VELOCITY AND TEMPERATURE PROFILES

Figure 4 demonstrates the velocity profiles in wall law coordinates. At x=50 mm two characteristic parts of the velocity distributions can be distinguished for case 1 (without a separation) and case 2 (laminar separation): a wall zone where $u^+ = y^+$ and a buffer zone between the wall zone and an external flow. The logarithmic law region is completely absent. Such profiles are typical for laminar and pseudo laminar boundary layers [13, 15].

In case 3 the appearance of a transitional separation promotes the expansion of the buffer zone on both sides, but the profile remains far from a turbulent one. In three cases described above the diffuser effect is not observed in distributions of velocity.

The substantial distortion of the velocity profiles takes place in cases 4 and 5 after a turbulent separation. It results in an expansion of the buffer zone in the region of lower y^+ and appearance of the usual for diffuser flows “loop” in the wake zone, enveloping the outer part of a dynamic boundary layer.

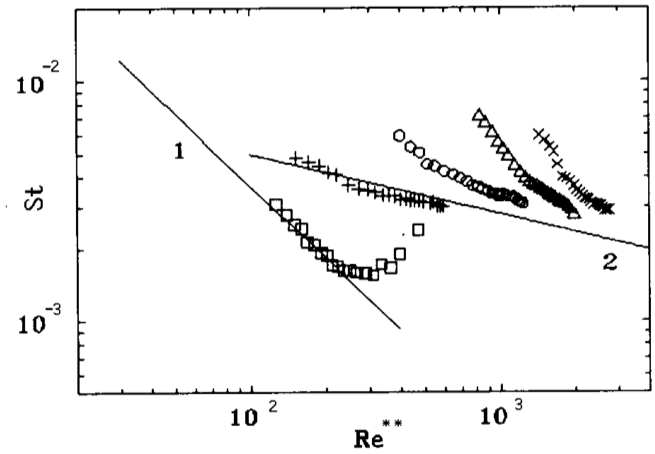

Fig. 3 Heat transfer coefficients versus Re^{**}. 1-eq. (2); 2-eq. (4)

Although the validity of the logarithmic law is questionable near a separation (see, e.g. [2, 4, 5, 11]), we use the following equation (5) for analysis of the obtained data and determination of friction coefficients by modified Clauser's method:

$$u^+ = 2.5\ln y^+ + 5.1\,. \qquad (5)$$

Along the zone of "slow" relaxation the existence of the region of the logarithmic law validity is experimentally confirmed by the given data: the velocity profiles become similar to those for quasiturbulent boundary layer differing in the values of wake parameters [13].

The transformation of temperature profiles is not identical to those for the velocity profiles described above. The experiments in a thermal boundary layer carried out for cases 3 and 4 show that near a separation at x=50 mm (Fig.4) as well as along the relaxation zone up to x=600 mm all the temperature profiles lie below the usual relation [17]:

$$\Theta^+ = 2.12\ln y^+ + 3.5\,. \qquad (6)$$

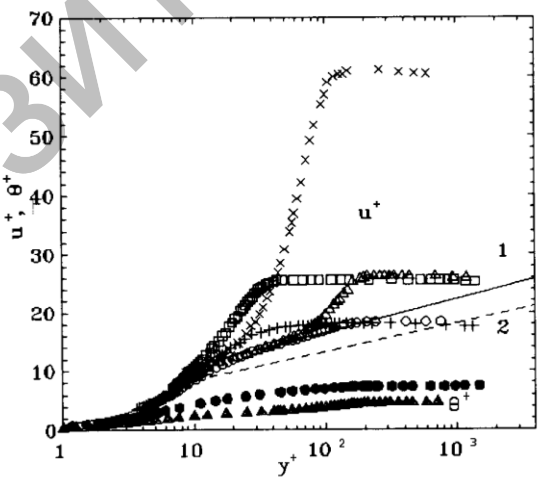

Fig. 4 Distributions of velocity and temperature at x=50 mm. 1-eq. (5); 2-eq. (6)

This is an evidence of nonuniversality of the temperature profiles in wall law coordinates. The tendency to universality of temperature profiles is observed only in coordinates $\Theta - y/\delta_t$ within the range of x under study. This fact confirms the conservative reaction of a temperature field to the effects of a different nature, including a separation.

CHARACTERISTIC THICKNESSES OF BOUNDARY LAYERS AND SHAPE PARAMETERS

After a separation of various types the thicknesses of a dynamic and thermal boundary layer (determined as usual by conditions $U_\delta = 0.99 U_e$ or $\Theta_\delta = 0.99 \Theta_e$) substantially exceed the ones in a "classical" turbulent layer (Figure 5), however the rate of their growth varies along the relaxation zone. In all cases under study in the presence of separation the thicknesses of a dynamic and thermal boundary layers change monotonously, their values practically coinciding.

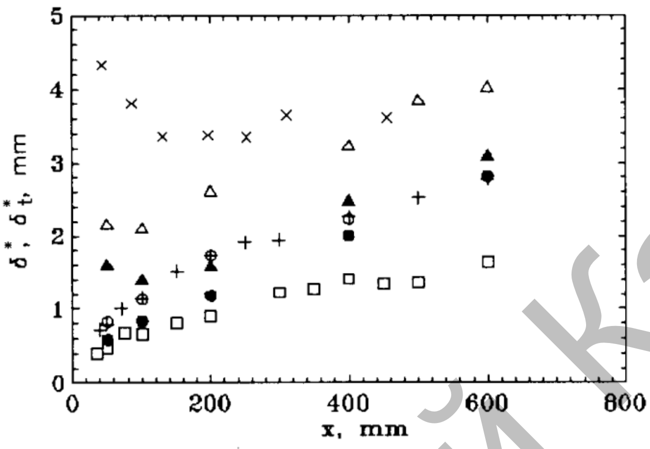

Fig. 5 Displacement thicknesses in dynamic and thermal boundary layer

The monotonous changes are also typical to momentum and enthalpy thicknesses. A different behaviour is observed for displacement thicknesses in case of a turbulent separation: their changes become nonmonotonous. Generally in a thermal boundary layer the values δ_t^* and δ_t^{**} are less than δ^* and δ^{**} in dynamic one. This fact confirms the different character of the recovery in a dynamic and thermal boundary layer particularly in inner and outer parts in zone of relaxation.

The distributions of shape parameters H and H_t (Figure 6) reflect the features of changes of characteristic thicknesses (displacement, momentum and enthalpy) described above.

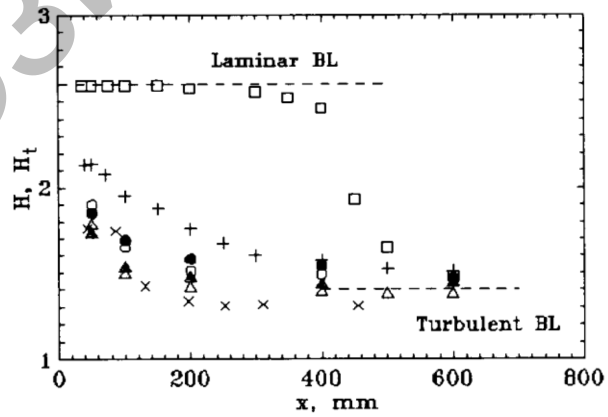

Fig. 6 Shape parameters in dynamic and thermal boundary layer

In case 1 when a separation is absent the main variations of H (from 2.59 to 1.48 at x=50 and 600 mm respectively) take place in the zone of laminar-turbulent transition owing to changes of flow regimes in a dynamic and thermal boundary layer. The quoted figures correspond to a "classical" laminar and turbulent (at comparatively low Reynolds numbers) boundary layer.

In case 2 after a laminar separation in region of development of a pseudolaminar boundary layer the values of H falls to 2.13 (at x=50 mm) and approaches to the same mentioned above at x=600 mm for a turbulent boundary layer.

In case 3 a transitional separation causes the similar changes with lower values of H=1.9 at x=50 mm.

It is necessary to note that in all three cases the diffuser effect at x=50 mm was not revealed in velocity profiles. The changes of H near reattachment are connected only with the separation type, i.e. the flow regimes in a separation region.

Otherwise after a turbulent separation in cases 4 and 5 the H values at x=50 mm (H=1.79) indicate on the diffuser effect; at x=600 mm the H values are slightly lower (H=1.38) in comparison with previous cases what is connected with the development of a quasiturbulent boundary layer. As shown in [13] the development of pseudolaminar or quasiturbulent boundary layers accompanies by decrease of the H values.

In a thermal boundary layer for cases 3 and 4 under study the distributions of H_t are completely similar to H (in particular H_t =1.85 and 1.74 at x=50 mm declining to 1.45 at x=600 mm). In our opinion one can take into account unpredictable changes of the characteristic thicknesses of a dynamic and thermal boundary layer in calculations of transport processes in complex flows and verifications of calculating models.

CONCLUSION

1. Owing to low free stream turbulence ($Tu_e \approx 0{,}2\%$) a “pure” separation was arisen and “worked” as generator of turbulence.

2. The separation caused the powerful structural changes near the wall, a separation “works” first of all as a generator of an external turbulence.

3. After separation an extremely slow recovery to a “classical” turbulent boundary layer with various rates of this gradual process in an inner and outer part of the boundary layers took place.

4. The length of relaxation in an outer part of the boundary layers was substantially longer than in an inner one.

5. Relaxation zone of a thermal boundary layer was shorter than of hydrodynamic one due to conservative reaction of thermal boundary layers to different disturbances including a separation.

6. The measurements also broadened the existing ideas about untraditional and to some extent unpredictable transformation of many important characteristics of a dynamic and thermal boundary layer in relaxation zone, concerning the distributions of heat and friction coefficients, mean velocities and temperatures, characteristic thicknesses, shape parameters, etc.

The presented data (stage 1) will be substantially added by characteristics of internal structure (fluctuations of velocity and temperature, spectral composition) as well as by based on the turbulent viscosity approach to calculation of heat transfer (stages 2, 3).

NOMENCLATURE

C_f friction coefficient
H, H_t shape parameters
t mean temperature
t^* dynamic temperature
U mean axial velocity
u^* velocity of friction
u^+ dimensionless velocity, U / u^*
x distance along a plate
y distance normal to a plate
y^+ dimensionless coordinate, yu^* / ν

Greek

δ, δ_t boundary layer thicknesses

δ^*, δ_t^* displacement thicknesses

δ^{**} momentum thickness

δ_t^{**} enthalpy thickness

ν viscosity

Θ, Θ^+ dimensionless temperature

$(t_w - t)/(t_w - t_e)$, $(t_w - t)/t^*$

Criteria

Re^{**} Reynolds number

St Stanton number

Subscripts

e external flow

r point of reattachment

t turbulent, thermal

w wall

δ outer edge of the boundary layer

0 $Tu_e = 0$

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