

UDC 532.517.3

## LOCAL 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 relaxing flow downstream of a separation of various types in case of low free stream turbulence  $Tu_\infty \approx 0.2\%$  and velocities of an external flow  $U_\infty \approx 5 - 10$  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 interceptor, 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:** relaxing flow, stream turbulence, wind tunnel, turbulent boundary layer, relaxation zone.

### INTRODUCTION

This paper is organic continuation of previous paper devoted to the integral characteristics of boundary layer in zone of relaxation after closed separation. As it was shown on the first stage of experimental investigation, at low free stream turbulence ( $Tu_\infty \approx 0,2\%$ ) a "pure" separation was arisen and "worked" as generator of turbulence. After separation an extremely slow recovery to a "classical" turbulent boundary layer with various rates of this gradual process in inner and outer parts of the boundary layers took place. Relaxation zone of a thermal boundary layer was shorter than of hydrodynamic one due to conservative reaction of thermal boundary layers to a separation.

In the previous paper there were presented many important characteristics of a dynamic and thermal boundary layer in relaxation zone (distributions of heat and friction coefficients, mean velocities and temperatures, characteristic thicknesses, shape parameters, etc.).

Given paper includes the results of two next stages of experimental investigation:

On the second stage the main attention will be paid to distributions of velocity and temperature fluctuations and their spectral composition.

On the third stage the common approach for calculation of heat transfer will be described using turbulent viscosity at the outer edge of a boundary layer.

### BRIEF DESCRIPTION OF EXPERIMENTS

The details of experiments are described in previous paper. Here it is useful to remind that there were investigated 5 cases of separation (see Table): turbulent separation of various intensity (cases 4 and 5), transitional separation (case 3) and laminar separation (case 2). In case 1 the separation was absent. In case 5 the inlet edge of working plate was blunt ( $2h=7.5$  mm); in other cases it was rounded ( $2h=3$  mm). In cases 1 and 2, 3 the length of interceptor was 60 and 25 mm correspondently. In cases 4, 5 interceptor was absent.

Table

Case	1	2	3	4	5
Des.	<b>PP0-60</b>	<b>PP0-25</b>	<b>PP0-25</b>	<b>PP0-0</b>	<b>PP0-0</b>
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	□ -	+ -	○ ●	△ ▲	× -

## VELOCITY AND TEMPERATURE FLUCTUATIONS

Analysis of longitudinal velocity fluctuation profiles permits to conclude that a separation of flow being the powerful wall generator of turbulence manifests itself first of all in the deformation of an outer edge of a dynamic boundary layer (Figure 1).

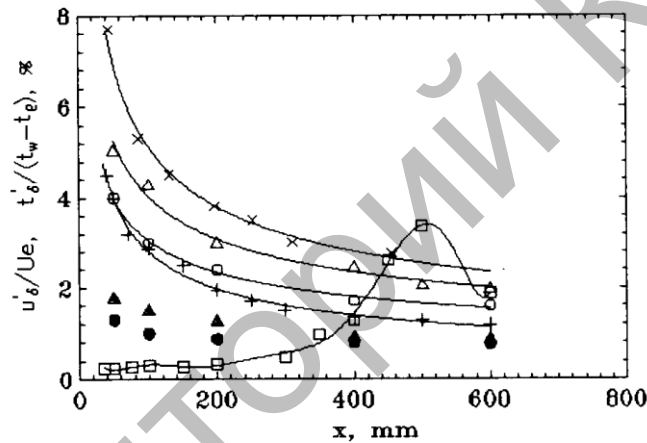


Fig. 1. Fluctuations of velocity longitudinal component and temperature at an outer edge of boundary layer

Thus in cases 5 and 4, when a turbulent separation of different intensity takes place, at an outer edge of a dynamic boundary layer the level of turbulence reaches to 7.7 and 5.1% at  $x=50$  mm declining to 2.8 and 2.0% at  $x=600$  mm despite a low free stream turbulence ( $Tu_e=0.2\%$ ). Such high values of turbulence are typical for external turbulized flows when turbulence is generated by special grids or perforated plates. Comparatively high levels of turbulence at the outer edge of a dynamic boundary layer are also observed in cases 2 and 3 for a laminar and transitional separation.

The usual decay laws for free stream turbulence after grids or other types of turbulence generators can be successfully used for an outer edge of a boundary layer [1-4]. On the basis of these laws it is possible to calculate the changes of kinetic turbulence energy, characteristic scales and turbulent viscosity, the latter decreasing along the zone of relaxation [4].

Another character of turbulence variations at an outer edge is observed for case 1 when a separation is absent and along the plate the growth of turbulence and turbulent viscosity takes place. Energy of fluctuations firstly increases linearly and then exponentially right up to maximum (to the end of a laminar-turbulent transition); only in a turbulent boundary layer it begins to decrease.

At that time for both cases 3 and 4 under study the level of temperature fluctuations at the outer edge of a thermal boundary layer is substantially lower than the level of velocity fluctuations (1.3 and 1.6% at  $x=50$  mm and 0.8-0.9% at  $x=600$  mm for cases 3 and 4). This evidences a weakening

of the correlation between fluctuations of velocity and temperature at an outer edge of the boundary layers along the relaxation zone.

Distributions of the longitudinal component of velocity fluctuations near the reattachment at  $x=50$  mm (Figures 2 and 3) show that in cases 5 and 4 after a turbulent separation there are two maxima of longitudinal fluctuations: the first of them is situated near the wall ( $y^+ \approx 13$ ) and the second is shifted into the outer region ( $y/\delta \approx 0.6$  and  $0.4$ ). The most part of turbulence energy is concentrated in the second maximum ( $u'/U_e \approx 19$  and  $15\%$  respectively). In the relaxation zone the second maxima gradually disappear and the fluctuation distributions become quasiturbulent-like with one maximum near the wall.

In cases 3 and 2 after a transitional or laminar separation the distribution of fluctuations factually has only one maximum reaching to  $u'/U_e \approx 13-14\%$  at  $y^+ \approx 13-14$ .

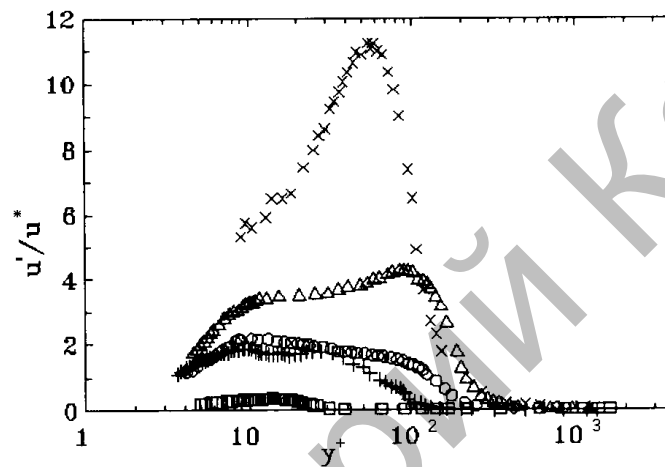


Fig. 2. Distributions of longitudinal fluctuations at  $x=50$  mm

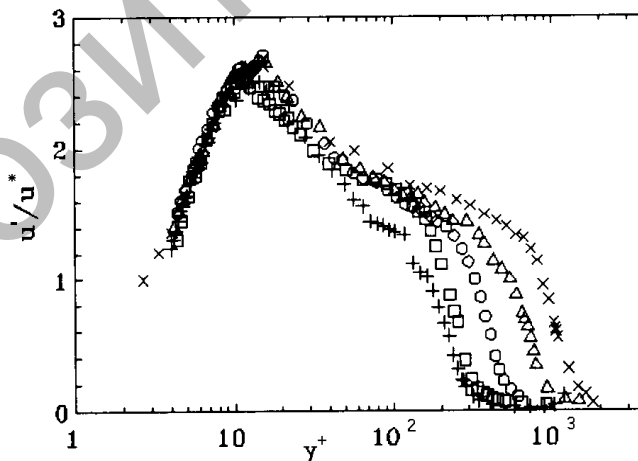


Fig. 3. Distributions of longitudinal fluctuations at  $x=600$  mm

These figures are typical for the first maximum of all four cases as well as for a “classical” turbulent boundary layer.

In case 1 when a separation is absent there is the growth of fluctuation energy along the plate with one maximum at  $y/\delta \approx 0.4$ . Such location of maximum of fluctuation energy indicates the existence of a pseudolaminar boundary layer [5].

Temperature fluctuations (Figure 4) are distributed through the thickness of a thermal boundary layer in another manner. In cases 4 and 3 after a turbulent and transitional separation near reattachment at  $x=50$  mm they have only one maximum ( $t'/(t_w - t_e) \approx 17$  and  $13\%$ ,  $t'/t^* \approx 0.9$ ) which practically lies on the wall ( $y^+ < 4$ ).

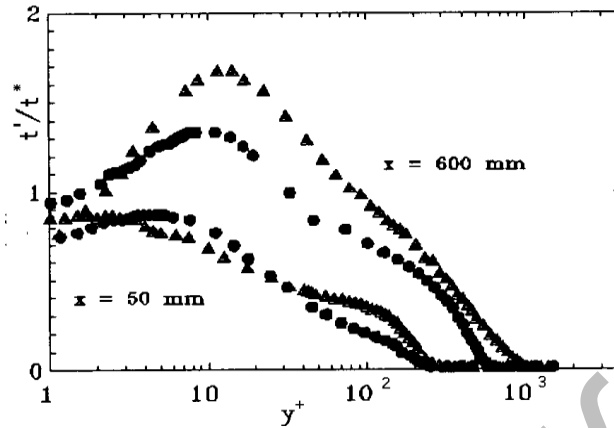


Fig. 4. Distributions of temperature fluctuations

Along the relaxation zone the maximum shifts from a wall to  $y^+ \approx 13$ , at  $x=600$  mm the values of  $t'/(t_w - t_e)$  decreasing to 10-12% and otherwise of  $t'/t^*$  increasing to 1.3-1.7. Note that in coordinate's  $t'/(t_w - t_e) - y/\delta_t$  profiles of fluctuation are close to universal. So, the field of temperature fluctuations forms earlier than velocity one, i.e. the length of a thermal and dynamic relaxation is different.

## CALCULATIONS OF HEAT TRANSFER

The method of calculation of heat transfer is developed for the zone of “slow” relaxation ( $x/x_r > 3$ ) in cases 5 and 4 when a turbulent separation takes place.

As it was pointed above, the approach of IET NASU assumes that the type of a separation as well as the enhancement of heat transfer in the relaxation zone is determined by dimensionless turbulent viscosity at an outer edge of a dynamic boundary layer in the section of reattachment ( $x = x_r$ ). The values of this viscosity can be calculated on the basis of an “energy-dissipation” turbulence model by two methods.

The first and the simplest of them suggests using the decay law of longitudinal fluctuations at an outer edge of the dynamic boundary layer developing after a separation. As our experience shows the description of this decay law can be made in a similar manner as it is accepted for free stream turbulence after two types of turbulence generators: grids or perforated plates installed directly in the test sections or before the confusers of the wind tunnels respectively.

The second method requires the measurements not only of longitudinal fluctuation energy but its spectral composition to determine the dissipation.

Two methods of determination of turbulent viscosity at the outer edge in the section of reattachment described above can be successfully used in the cases of low free stream turbulence when its scale does not influence on the developing boundary layers. As shown in studies of IET NASU [1, 2, 4, 6, 7] in cases of high free stream turbulence and its large relative scales so called “overlay” arises between an outer edge of a dynamic boundary layer and turbulized external flow. In overlay an attenuation of transport properties of the external flow takes place. It results in anisotropy at an outer edge of a dynamic boundary layer and requires the development of new schemes of calculation or modification of existing ones, taking into account the scale influence

described above. Problem is actual in case of high free stream turbulence arising in passage part of power equipment.

In the given investigation when a separation was absent ( $v_{t\delta r}/\nu \approx 0$ ) a typical laminar-turbulent transition took place along a plate surface. The growth of  $v_{t\delta r}/\nu$  to  $\sim 5$  caused a laminar separation promoting after it the emergence of the bypass transition and further development of a quasiturbulent-like boundary layer. At  $v_{t\delta r}/\nu \approx 20$  a transitional separation as well as at  $v_{t\delta r}/\nu > 30$  a turbulent separation of different intensity also transformed to the quasiturbulent-like boundary layers. In the latter case at  $Re^{**} = \text{const}$  the enhancement of heat transfer was described by the similarity equation (1) based on the ratio of turbulent viscosity at an outer edge of a boundary layer in the section of reattachment to turbulent viscosity in a "classical" turbulent boundary layer ( $v_{t\delta r}/v_{t0}$ ).

In the first approximation in zone of "slow" relaxation after a turbulent separation at  $x/x_r > 3.3$  (cases 5 and 4) at  $Re^{**} = \text{const}$  the current values of heat transfer coefficients ( $St$ ) can be calculated by the following relation:

$$St/St_0 = 1 + 0.2(v_{t\delta r}/v_{t0})^3, \quad (1)$$

where the  $St_0$  values are determined for a "classical" turbulent boundary layer. The relation (1) contains also the turbulent viscosity  $v_{t0}$  generated near the wall in a turbulent boundary layer and calculated on the basis of known recommendation, for example:

$$v_{t0} = 0.0168U_e\delta^{**}. \quad (2)$$

It is necessary to note that the choice of reference conditions is very important in generalization of experimental results. The relation (1) has been obtained at  $Re^{**} = \text{const}$ .

The comparison of data under the reference condition  $Re^{**} = \text{const}$  in fact leads to a virtual overstating of coefficients of heat transfer intensification  $St/St_0$  (due to the growth of a momentum thickness with strengthening a turbulent separation) and as a consequence to the shift of the used reference dependence for a "classical" turbulent boundary layer into the range of higher  $Re^{**}$ . However in our opinion such choice is rather grounded by local presentation of experimental data when many uncertainties connected with the initial conditions are excluded owing to use of momentum thickness (not current length  $x$ ) as a determining dimension.

## FILTRATION PROPERTIES

A deep insight into the mechanism of development of a boundary layer after a separation is given by so called filtration coefficient: the ratio of the spectral power at the given point in the boundary layer,  $E_u(n)$ , to its value at the outer edge of the boundary layer,  $E_u(n)_\delta$ , at the same frequency,  $n$ .

The distributions of filtration coefficients for the longitudinal component of velocity fluctuations after a turbulent separation in the beginning of zone of "slow" relaxation at  $x=50$  mm (Figure 5, case 4) indicate the existence of the one-directed flow of the kinetic turbulence energy directed from the boundary layer into the external flow at all frequencies. The maxima of local energies are located at  $y/\delta \approx 0.4$ , as it takes place for integral energy of fluctuations, i.e. practically coincide with the position of the second maximum in distributions of longitudinal fluctuations. Such behavior of filtration coefficients is typical for the flows with a longitudinal unfavorable pressure gradient [6].

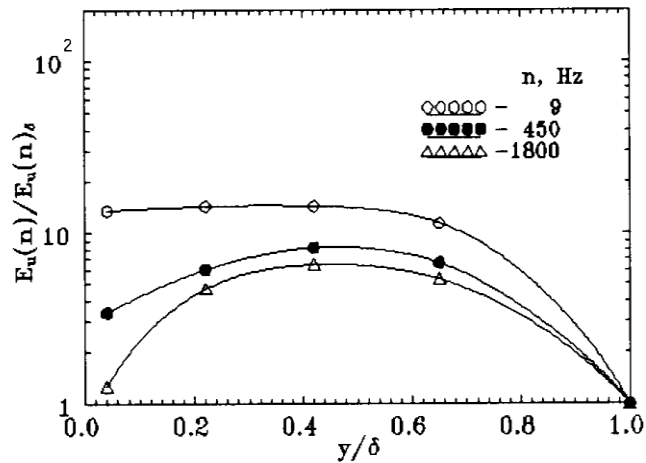


Fig. 5. Filtration coefficients after turbulent separation at  $x=50$  mm

After a transitional separation the energy transfer into the external flow is also observed at all frequencies, however the character of coefficient filtration distributions is another. In range of low and moderate frequencies the maxima of local energies are placed near the wall ( $y^+ \approx 13$ ), and coincide with the same for the integral energy, whereas at high frequencies they shift up to  $y/\delta \approx 0.3$  from wall. Thus a pseudolaminar boundary layer or weak diffuser effect manifest themselves only at high frequencies, because they are practically absent in the changes of another characteristics (in the first turn in the velocity distributions at  $x=50$  mm).

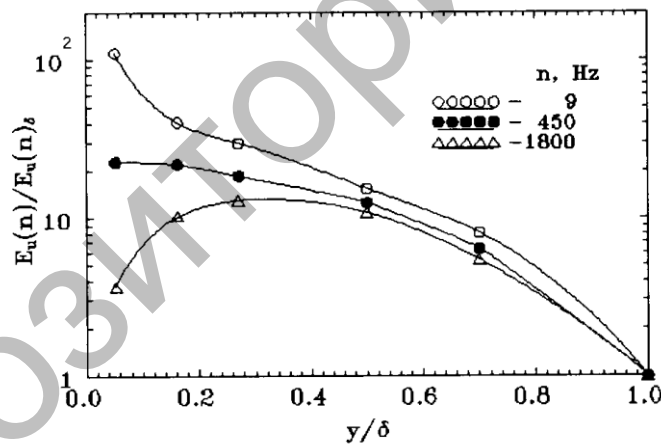


Fig. 6. Filtration coefficients after transitional separation at  $x=50$  mm

In both cases described above at  $x=600$  mm there is only the drain of energy into the external flow, maxima of local energies at all frequencies being located at  $y^+ \approx 13$ , what confirms an existence of a turbulent or quasiturbulent - like boundary layer along the zone of “slow” relaxation.

## CONCLUSION

The presented results of the experimental study of the characteristics of the relaxing flow downstream of a separation of various types confirm the validity of approach developed in IET NASU for estimation of transport properties of complex flows. Due to this approach turbulent viscosity at the outer edge of a dynamic boundary layer in the section of reattachment  $\nu_{t\delta^*}/\nu$  was

chosen as the basic criterion determining in the first approximation the type of a separation (laminar, transitional or turbulent) and its intensity.

The measurements of local structure in zone of relaxation show the different velocities of approximation to classical turbulent boundary layer of such parameters as longitudinal and temperature fluctuations. The analysis of power spectra permitted to conclude that memory effects manifest themselves differently depending on frequency: at some frequencies the main features of prehistory preserve when at others they disappear. In our opinion this fact is very important and demands further experimental investigations for penetration into the internal mechanism of relaxation and improvement of existing turbulence models.

## NOMENCLATURE

$t$	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, $yu^*/\nu$
<i>Greek</i>	
$\delta, \delta_t$	boundary layer thicknesses
$\nu$	viscosity
<i>Criteria</i>	
$Re^{**}$	Reynolds number
$St$	Stanton number
<i>Subscripts</i>	
$e$	external flow
$r$	point of reattachment
$t$	turbulent, thermal
$w$	wall
$\delta$	outer edge of the boundary layer
$0$	$Tu_e = 0$

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