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Velocity and turbulence measurements in a separating boundary layer with laser Doppler velocimetry

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ABSTRACT

The present paper reports the results of a detailed experimental study on a large-scale flat plate with prescribed adverse pressure gradient producing a turbulent boundary layer separation.

Laser Doppler Velocimetry has been adopted, being a powerful technique for accurate turbulent boundary layer investigations, particularly when separation occurs and other techniques, such as hot-wire or hot-film anemometers, cannot recognize when reverse flow happens. In order to obtain measurements with low statistical errors in separating flow regions, an appropriate mean data rate was adopted based on flow integral time scales.

Both the velocity components in streamwise and normal directions have been measured. Mean values and higher order moments have been reported in contour plots with mean velocity vector maps superimposed, in order to provide an overview of the flowfield behaviour inside the test section and to underline the effects induced by separation.

NOMENCLATURE

C_f	skin friction coefficient $=\frac{\tau_w}{\frac{1}{2}\rho U^2}$
e	statistical error
f	frequency
f_s	data rate
H_{12}	shape factor $=\frac{\delta^*}{\vartheta}$
K	overall acceleration factor = $\frac{\nu}{U_0^2}\frac{(U_1-U_0)}{(X_1-X_0)}$
N	number of samples
pdf	probability density function
Re_θ	momentum thickness Reynolds number = $U_0\theta/\nu$
rms(u')	root mean square of the streamwise velocity fluctuations
rms(v')	root mean square of the normal velocity fluctuations
S	power spectral density
Sk(u)	skewness of the streamwise velocity = $\frac{1}{N}\sum_{i=1}^{N}\left(\frac{u_i-\bar{u}}{rms(u')}\right)^3$
t	time

T_i	integral time scale
Tu	free-stream turbulence intensity = rms$(u')/U$
U	free-stream velocity
u	streamwise velocity
u_τ	wall friction velocity $=\sqrt{\tau_w/\rho}$
u^+	boundary layer inner variable $=\dfrac{\overline{u}}{u_\tau}$
$-\rho\,\overline{u'v'}$	Reynolds shear stress
v	velocity component in the y direction
x	axial coordinate from the test section inlet
y	distance from the wall
y^+	boundary layer inner variable $=y\dfrac{u_\tau}{\nu}$
δ	boundary layer thickness
δ^*	displacement thickness $=\int_0^\delta (1-\dfrac{\overline{u}}{U})dy$
θ	momentum thickness $=\int_0^\delta \dfrac{\overline{u}}{U}(1-\dfrac{\overline{u}}{U})dy$
ν	kinematic viscosity
ρ	density
τ_w	wall shear stress

Subscripts and superscripts

$\bar{}$	time averaged quantity
$'$	fluctuating quantity

1. INTRODUCTION

Experimental studies focused on boundary layer separation control for gas turbine applications are presently underway at the Aerodynamics and Turbomachinery Laboratory of University of Genova. This research originates from the modern tendency, in the aircraft engines design, towards weight and dimensions reduction, that may lead to high longitudinal adverse pressure gradients within the internal ducts, with the consequent occurrence of boundary layer separation. The application of appropriate flow control techniques may prevent boundary layer separation. Therefore experimental studies aimed at the flow control techniques development are of primary importance.

The present paper concerns the experimental investigation of a separated boundary layer on a flat plate with adverse pressure gradient, preliminary step for the application of flow control techniques.

In a previous authors' work (Canepa et al.[1]), the separated boundary layer has been investigated by means of Particle Image Velocimetry. P.I.V. measurements provided instantaneous flow fields, hence allowing the capture of flow organized structures present inside the separated boundary layer. In the present work, Laser Doppler Velocimetry has been employed, to complete the separating turbulent boundary layer analysis.

The L.D.V. technique allows a higher spatial resolution even very close to the wall, providing an accurate description of the flow in terms of wall coordinates, as well as a high statistical accuracy, necessary for a detailed investigation of the separation mechanisms.

Data obtained will be discussed in the following sections, where distributions of mean velocity, Reynolds stresses, and skewness of the streamwise velocity component are shown.

2. EXPERIMENTAL APPARATUS

The facility, described in detail by Canepa et al.[2], consists of an open-loop blow-down wind tunnel (Fig. 1) installed at the Aerodynamics and Turbomachinery Laboratory of the University of Genova.

The test section (Fig. 2) was designed to provide several adverse pressure gradients typical of aeroengine intermediate ducts. The boundary layer flow develops on a large-scale flat plate 1700 mm long and 400 mm wide, with the leading edge located about 600 mm upstream of the test section inlet, in order to obtain a fully turbulent boundary layer inside the test section. The inlet test section height is 196 mm. Boundary layer suction has been applied both to the lateral and to the top wall boundary layers upstream of the test section inlet in order to avoid section blockage and to obtain a two-dimensional flow inside the test section. To avoid separation on the inclined top wall, the boundary layer was controlled by suction also on this wall.

Figure 1. Experimental apparatus

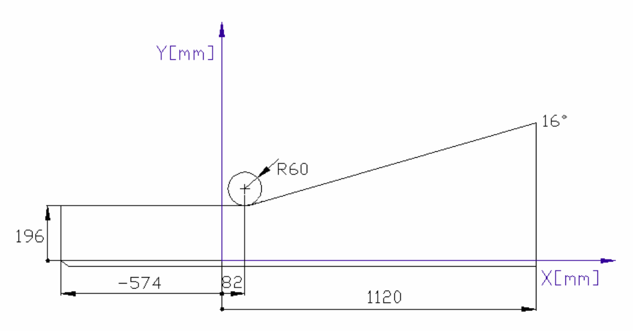

Figure 2. Test section scheme

For the experiment discussed in this paper the test section top wall was regulated with an inclination of 16°, which corresponds to an ideal overall acceleration factor K value of $-3.16 \cdot 10^{-7}$. This parameter represents the non dimensional velocity gradient of an ideal one-dimensional flow between the inlet and the outlet of the test section. The mean velocity at the test section inlet was 28.1 m/s. The fundamental boundary layer parameters and free-stream turbulence intensity at the inlet section are summarized in Table 1.

Table 1. Inlet section flow parameters

δ	ϑ	H_{12}	Re_{ϑ}	C_f	Tu
80 mm	5.6 mm	1.24	11000	0.0032	1%

3. MEASURING TECHNIQUE

3.1 Laser Doppler velocimetry instrumentation

A four beams two colours laser Doppler velocimeter (Dantec Fiber Flow), in backward scatter configuration, was employed for the present investigation. The light sources are two diode-pumped solid state lasers with a power of 200mW each one. The two pairs of green and blue beams, employed to investigate the two velocity components, have respectively wave lengths of 532 nm and 488 nm. The frequency of one of each pair of beams was shifted of 40 MHz by a Bragg cell. The probe consists of an optical transducer head of 60 mm diameter, with a focal length of 300 mm and a beam separation of 38 mm, connected to the emitting optics and to the photomultipliers by means of optic fibres. The beam intersection angle is 7.4°. The fringe separation is 4.1 μm for the green pair of beams and 3.8 μm for the blue one.

The probe volume is 0.09 mm x 0.09 mm x 1.4 mm. Flow was seeded by mineral oil droplets with a mean diameter of 1.5 μm. To process bursts, two Dantec Enhanced Burst Spectrum Analysers were employed. For each measurement point 30000 samples were collected with a maximum record length in time of 120 s.

3.2 Experiment organization

The boundary layer developing over the flat plate was studied by means of 14 traverses normal to the flat plate in the center plane. The traverses were located at axial positions ranging between 0 and 600 mm from the test section inlet. Each boundary layer traverse was constituted by 103 measuring points, with the first point at a distance of 50 μm from the wall and a distance between adjacent points of 50 μm in the region of the boundary layer close to the wall and progressively increased in the outer part.

The probe volume was oriented with the larger dimension along the plate spanwise direction in order to have better spatial resolution in the x and y directions. The LDV probe was traversed using a three-axis computer controlled probe traversing mechanism with a minimum linear translation step of 8μm.

The measurements of the two velocity components were made in coincidence mode, in order to evaluate the Reynolds shear stress. For each measuring point 30000 samples were collected to obtain accurate statistical analysis.

3.3 LDV experimental uncertainty

A specific evaluation of errors for LDV frequency domain processors is given by Modarress et al.[3]. The experimental uncertainty was evaluated to be less than 1 percent of the mean velocity. Statistical moments were weight-averaged with transit time to avoid statistical bias, as proposed by Karpuk and Tiederman[4].

Thanks to the large number of samples (30000) the statistical uncertainty on the averaged velocity due to finite number of samples was estimated better than ± 4 % for a probability of 95 % and a local turbulence intensity of 100 % (rms of the velocity equal to mean velocity) in the near wall region, where turbulence intensities based on the local mean velocity as large as 100 per cent can occur.

In order to obtain high accuracy also in the boundary layer separating region, the data rate has been reduced, considering the local integral length scale of the flow, according to George[5], as briefly described in the following section. In fact, integral length scale increases significantly in separating boundary layers, due to the existence of large scale vortical structures that characterize the intermittent detachment process (Simpson[6]).

In the region next to the wall, a false turbulence due to the velocity gradient and finite dimension of the probe volume can constitute a significant part of the measured streamwise velocity variance. Karpuk and Tiederman[4] have analysed in detail this problem. The rms of streamwise velocity fluctuations has been corrected accordingly to their analysis.

3.4 Statistical error in a separating boundary layer

A problem that should be considered, when measuring in a separating turbulent boundary layer by means of the LDV technique, concerns the statistical errors on mean velocity and higher order moments, that could occur in the separated zone. This problem, has been widely discussed in a previous authors' work (Satta et al.[7]).

An accurate statistical analysis requires statistically independent samples. For this reason the sampling period should be not smaller than the integral time scale of the flow. For this purpose, a first measurement campaign at the maximum data rate obtainable (ranging from 500 to 3000 Hz) has been carried out in order to evaluate the integral time scale of the flow from the power spectral density of the velocity (Eq. 1):

$$T_i = \frac{S_{f \to 0}}{2\overline{u'^2}} \tag{1}$$

The color plot reported in Fig. 3 shows higher values of the integral time scale occurring inside the reverse flow region, due to the formation of large scale flow structures caused by boundary layer separation.

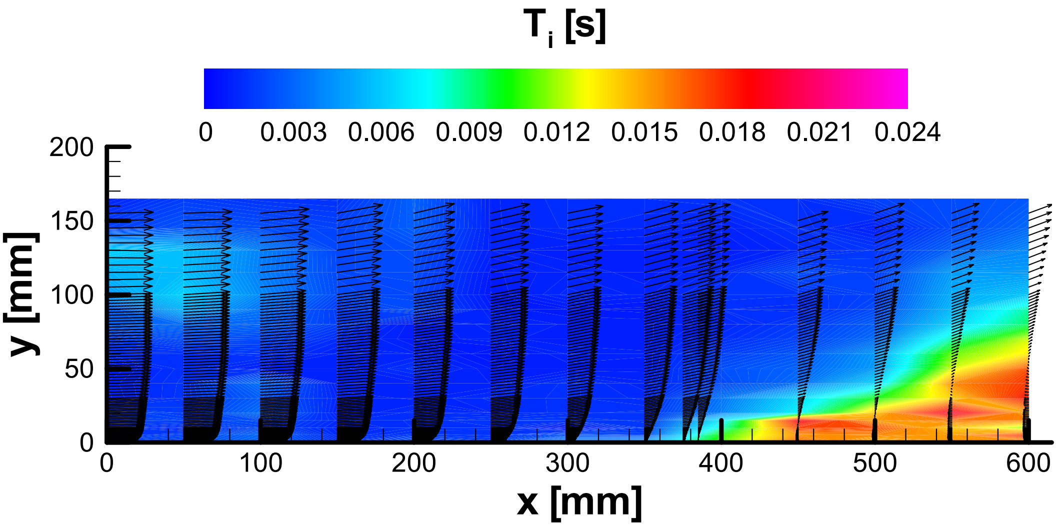

Figure 3. Flow integral time scales color plot

Since in the statistical error evaluation of the mean velocity proposed by George [8] (Eq. 2), both the integral time scale (T_i) and the data rate (f_s) are present in the dividend:

$$e^2 = \frac{(1+2f_s T_i)}{N}(rms(u')/\bar{u})^2 \tag{2}$$

when the integral time scale increases, the data rate should be reduced in order to decrease the statistical error. For this reason, another measurement campaign with lower data rate (100-500 Hz) has been carried out. Reducing the data rate, the independent samples increase and the statistical errors, especially for second order velocity moments, decrease.

4. RESULTS AND DISCUSSION

4.1 Mean velocity distributions

To get a detailed description of the boundary layer development over the bottom flat plate, mean velocity components, and their higher order moments, have been reported in color plots.

The time-averaged velocity distribution is shown in Fig. 4, where the velocity vectors have been superimposed to the contour plot of the mean streamwise velocity. A streamwise reduction of the freestream velocity associated to the pressure gradient within the duct is clearly detectable from the plot. The adverse pressure gradient that the flow experiments along the duct provokes the occurrence of boundary layer separation at a distance equal to 385 mm from the test section inlet, as shown by the velocity vector distribution. In fact, the velocity gradients normal to the wall tend to decrease moving downstream, just up to the detachment point. Downstream of it, in the back flow region, zero mean velocity location tends to move away from the wall, and the portion of flow affected by negative streamwise velocity becomes wider as much as the axial coordinate increases. Boundary layer is subjected to a strong thickening, when separation occurs.

Moreover, a positive normal velocity component is present in the freestream region due to the top wall inclination, the top wall boundary layer suction, and the flat plate boundary layer blockage. This velocity component behaviour is even more evident in the contour plot of the normal velocity component (Fig. 5). On the other side, downstream of the detachment point, between the wall and the zero time averaged streamwise velocity, this normal velocity component vanishes, and the reverse flow seems to move nearly parallel to the wall.

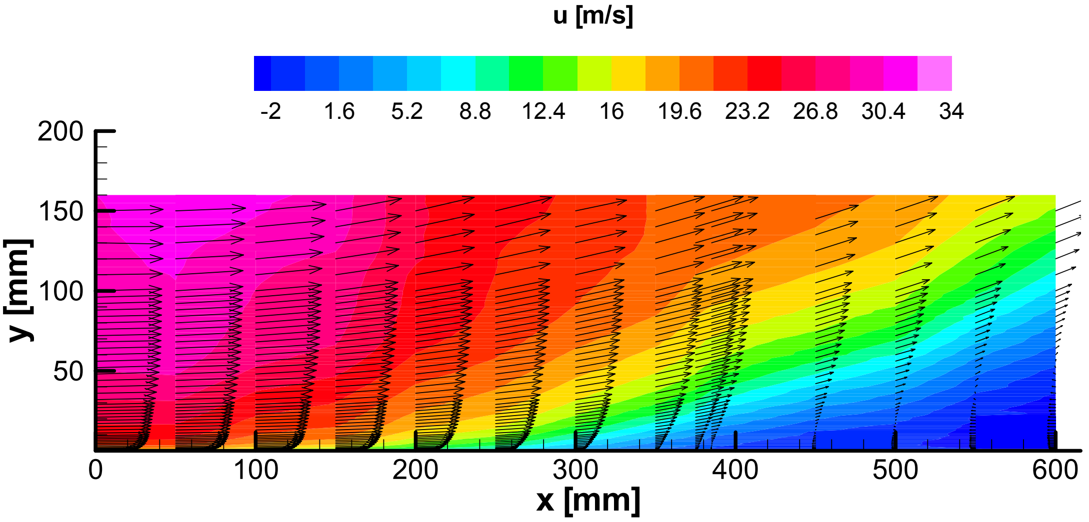

Figure 4. Vector plot and contours of time-averaged streamwise velocity

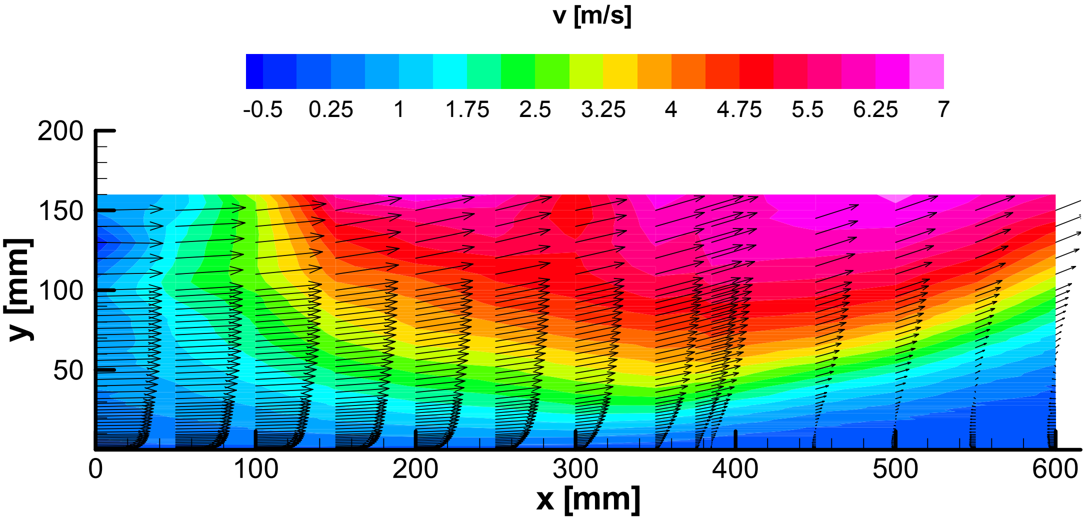

Figure 5. Vector plot and contours of time-averaged velocity component normal to the wall

4.2 Wall coordinate profiles

To have a more in depth understanding of the behaviour of the separating boundary layer subjected to a strong adverse pressure gradient, the velocity distributions at three different axial locations have been plotted also in wall coordinates. The experimental data are compared to the theoretical laws valid for turbulent boundary layers developing over a flat plate in Fig. 6. The first plot, referred to an axial location where the duct has still a constant cross section (x=50 mm), shows a very good agreement between experimental and theoretical curves.

Increasing the axial coordinate (x=200 mm), it is possible to observe a progressive reduction of the log-law region, due to the strong adverse pressure gradient and the consequent reduction of the wall shear stress. This feature is typical of turbulent boundary layers with strong adverse pressure gradients (e.g. White[9]). Moving towards the detachment point (x = 375 mm, separation detected at x=385 mm), only the viscous sublayer law is followed. Since buffer and logarithmic laws are not followed in separating flow regions, here near wall measurements are necessary to allow wall shear stress evaluation.

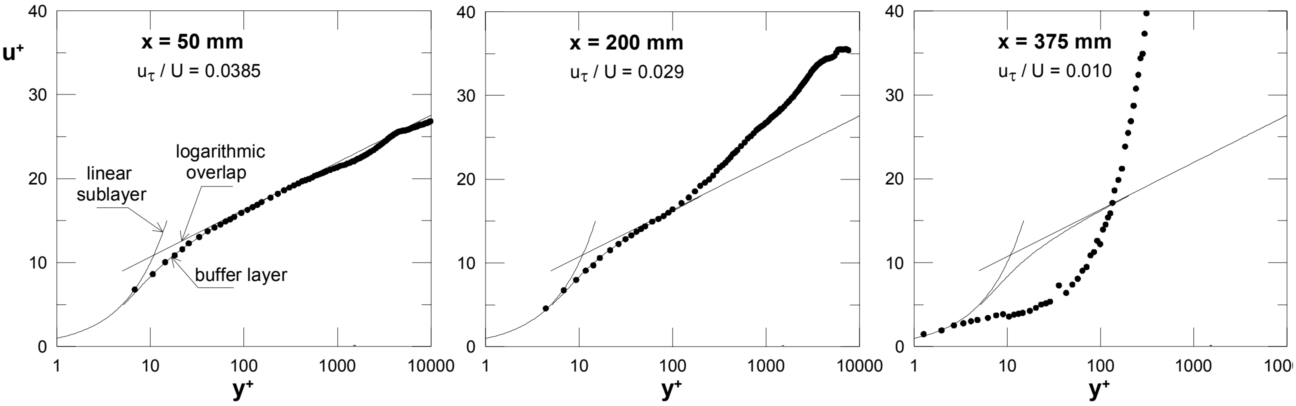

Figure 6. Wall coordinates velocity profiles

4.3 Turbulence measurements

Root mean square of the velocity fluctuations in both streamwise and normal directions have been measured.

Analyzing the rms of the streamwise velocity (Fig. 7), it is possible to observe how upstream of the detachment point the rms distribution is typical of a turbulent boundary layer[10], presenting the higher values in the proximity of the wall. On the contrary, moving toward the detachment point, maximum values tend to move away from the wall, and, within the separated region, the highest rms values are detectable adjacent to the curve obtained joining points where the mean velocity is zero, as shown in Fig. 7, that reports the rms contours along the duct overimposed to the time-averaged velocity vector distributions. These high rms values, associated to the boundary of the separated region, are due mainly to the fluctuations at low frequencies of the instantaneous velocity, that presents alternatively positive and negative values. The rms maximum occurs for a value of *y* higher than those corresponding to zero mean velocity. This is probably imputable to oscillations of the separated zone in the *y* direction.

Comparing the root mean square of the velocity fluctuations obtained in the streamwise and in the normal directions (Fig. 8), a high turbulence anisotropy is clearly visible, since the rms maximum of the streamwise velocity is about twice that of the normal velocity. Nevertheless, both the plots present the same qualitative distribution.

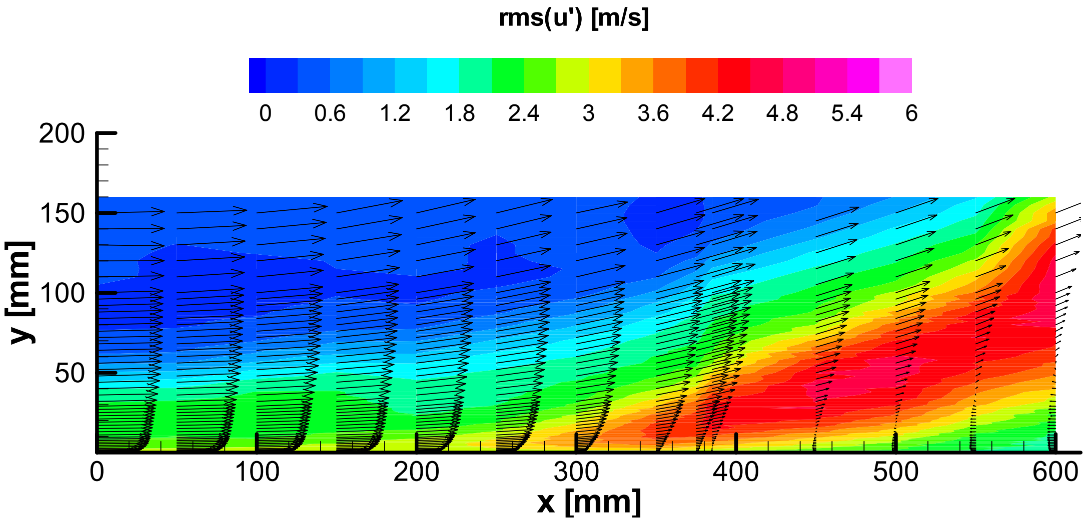

Figure 7. Rms of the streamwise velocity contour and time-averaged velocity vector plot

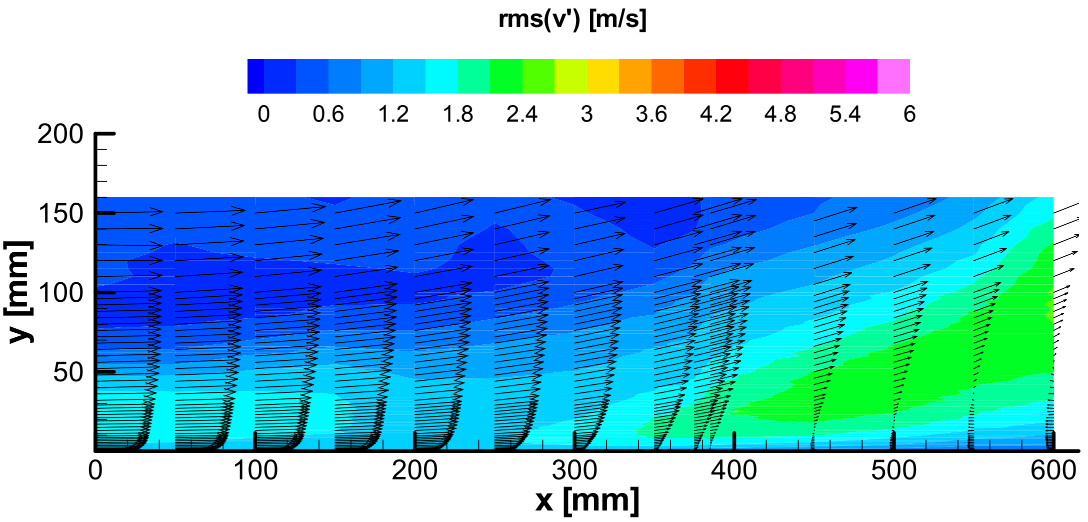

Figure 8. Rms of the velocity normal to the wall contour and mean velocity vector plot

4.4 Reynolds shear stress measurements

Upstream of the detachment point, also the Reynolds shear stress (Fig. 9) presents a distribution typical of turbulent boundary layers. In fact, in the attached flow, Reynolds shear stress maximum values occur in the proximity of the wall. On the contrary, moving downstream beyond the separation onset, the Reynolds shear stress maximum tends to decrease and moves away from the wall. Moreover, in the separated region (downstream of x = 385 mm), a reduction of the normal to the wall Reynolds shear stress gradient may be also observed, causing a reduction of the re-energizing action on the mean flow, that in the attached boundary layer prevents separation.

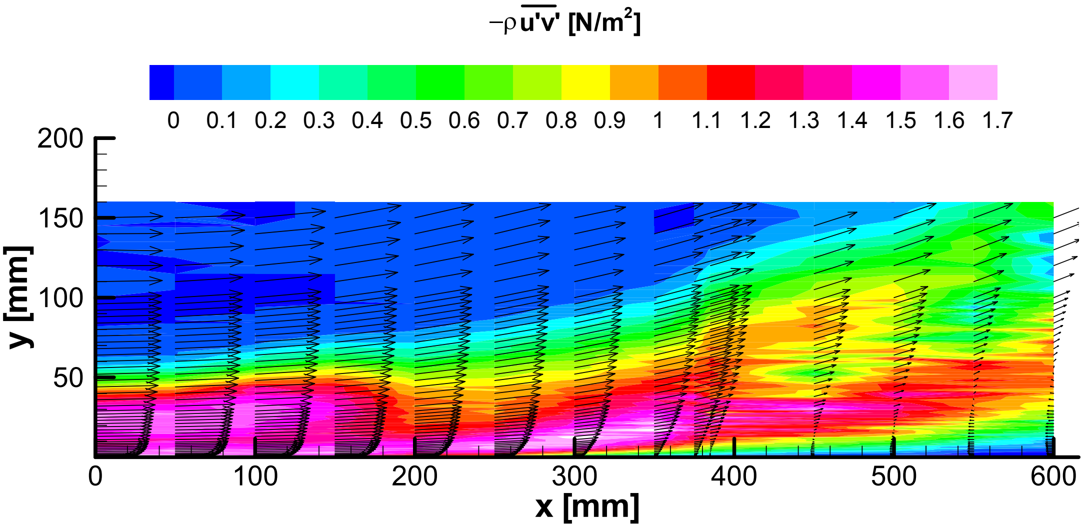

Figure 9. Reynolds shear stress contour and mean velocity vector plot

4.5 Skewness distribution

In Fig. 10, the skewness distribution is reported. Since the third statistical moment characterizes the degree of asymmetry of a probability distribution around its mean, it constitutes a way to detect the boundary layer thickness development within the duct. In fact, boundary layer edge is detectable where the skewness changes from highly negative values, typical of the boundary layer particles near to the edge, to zero values, typical of the freestream flow.

Two examples of the velocity time traces measured at x = 350 mm, near to the boundary layer edge (y = 98 mm), and inside the freestream (y = 125 mm) are shown in Figs. 11 and 12 respectively. At y = 98 mm, large negative peaks with respect to the mean value are present (corresponding to negative skewness values), while at y = 125 mm, the time trace does not show any prevalence of positive or negative peaks (zero skewness).

The skewness distribution confirms the strong thickening of the boundary layer associated to the turbulent separation, as already noted from the mean velocity vector plots. Furthermore, an increase of the boundary layer thickness growing rate is noticeable downstream of the detachment point.

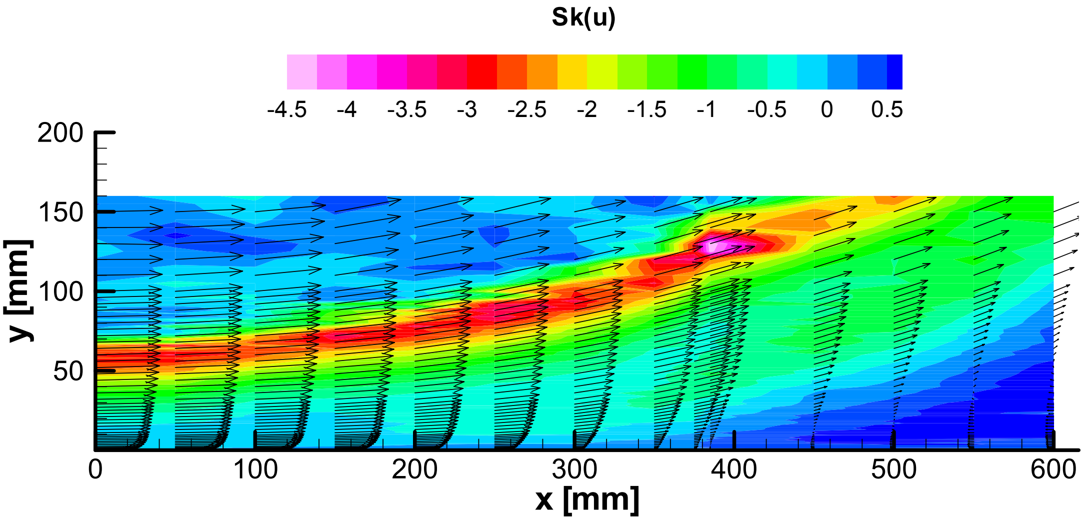

Figure 10. Skewness contour and mean velocity vector plot

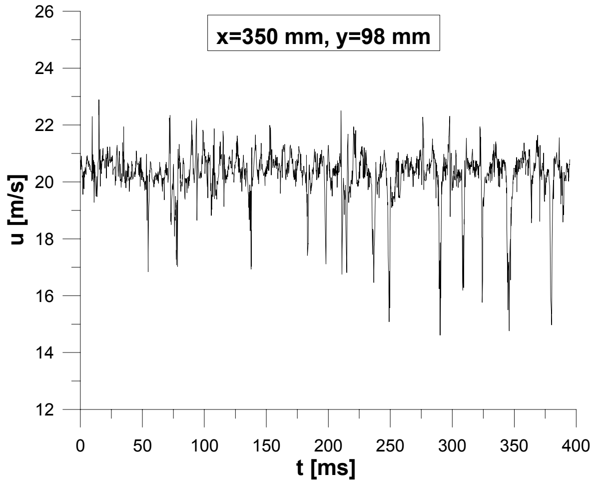

Figure 11. Velocity time trace at x=350 mm and y=98 mm

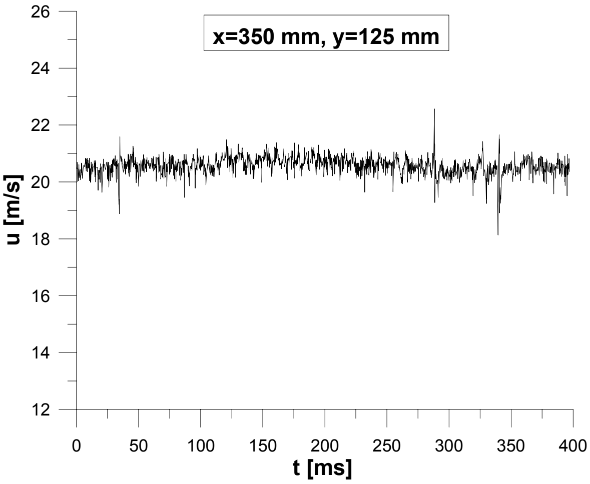

Figure 12. Velocity time trace at x=350 mm and y=125 mm

Inside the back flow region, the skewness distribution shows an almost symmetrical velocity distribution ($Sk(u)$ = 0), as confirmed also by an example of time trace measured at x=500 mm, y=4mm (Fig. 13).

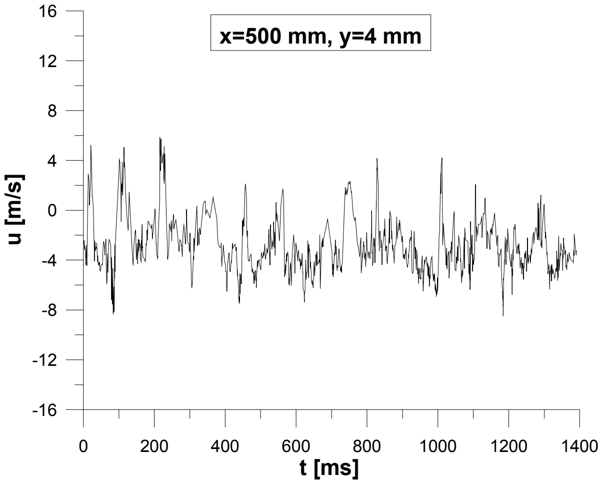

Figure 13. Velocity time trace measured inside the back flow region

5. CONCLUSIONS

The boundary layer developing over a flat plate subjected to an adverse pressure gradient, with an ideal overall acceleration factor K equal to $-3.16 \cdot 10^{-7}$, has been investigated by means of Laser Doppler Velocimetry.

Mean velocity contour plots have shown the occurrence of boundary layer separation. Positive normal velocity component was present outside of the back flow region, because of the top wall inclination, the top wall boundary layer suction, and the flat plate boundary layer blockage.

Velocity rms contour plots have shown maximum values of turbulent fluctuations occurring in the proximity of the boundary of the back flow region, probably due to the fluctuations at low frequencies of the instantaneous velocity that presents alternatively positive and negative values. Moreover, comparing the root mean square of both mean and normal velocities, a high turbulence anisotropy came out.

Reynolds shear stress and its gradient presented a rapid reduction in the separated region, causing a decreasing of the near-wall flow energizing effect, with respect to the condition of attached boundary layer.

A strong boundary layer thickening inside the separated region has been observed by the skewness colour plot, and an almost symmetrical velocity distribution has been detected inside the back flow region.

The present results describe in detail the development of a separating turbulent boundary layer and may constitute a test case useful for the numerical codes validation.

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