Evolution of the Anisotropy Over a Flat plate With Suction

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Abstract:

Laser Doppler Velocity measurements are carried out in a turbulent boundary layer subjected to a concentrated wall suction (through a porous strip). The measurements are taken over a longitudinal distance of nine times the incoming boundary layer thickness behind the suction strip. The results indicate that the state of the perturbed boundary layer departs from that of the pseudo-equilibrium of the unperturbed layer.

It is found that suction alters the redistribution of the turbulent kinetic energy between its components. Relative to the no suction case, the longitudinal Reynolds stress contributes more to k than the other two normal Reynolds stresses; in the outer region, its contribution is reduced. The alteration of the energy transfer between the turbulent kinetic energy components reflects structural changes in the boundary layer. This is observed in the anisotropy of the Reynolds stresses, which depart from the non disturbed boundary layer. With suction, the anisotropy level in the near wall region appears to be stronger than that of the undisturbed layer. It is argued that the mean shear induced by suction on the flow is responsible for the alteration of the anisotropy.

The variation of the anisotropy of the layer will make the development of a turbulence model quite difficult for the flow behind suction. In that respect, a turbulence model will reproduce well the effects of the suction on the boundary layer, if the model captures the effect of suction on the anisotropy of the Reynolds stresses.

INTRODUCTION

The perturbation of a turbulent boundary layer through the application of wall suction presents several advantages. From an engineering point of view, this can be used for controlling the boundary layer with the view to either relaminarise (Antonia et al., 1995, Oyewola et al., 2001) or postpone the separation (Fiedler and Fernholz, 1990) or even controlling the level of skin friction and total drag. From a fundamental viewpoint, one can gain information of the dynamics of the boundary layer by studying its response to suction. Such a response can be reflected in the level of the anisotropy of the Reynolds stresses, b_{ij} $(= u_i u_j/k - 2/3 d_j$, where $u_i u_j$ are the Reynolds stress components, $k = \frac{1}{2} u_i u_i$ and d_j is the delta function). For example, when all b_{ij} components are null, the turbulence is isotropic indicating that any coherent structures present in the flow are statistically isotropic.

The study here focuses on the effects suction can have on the Reynolds stress anisotropy tensor with the view to gain some insight into the mechanism by which the anisotropy plays a role in the production of turbulence energy, through the term $-2k b_{ij} S_{ij}$ (S_{ij} is the strain rate tensor), in a turbulent boundary layer. Such knowledge is fundamental because modelling the effects of the anisotropy is one of the most important and delicate element in the development of turbulence models. Recently, Oyewola et al. (2004) presented hot-wire measurements of the b_{ij} components in a turbulent boundary layer subjected to wall suction. Their results indicate that behind the suction strip the b_{ij} components undergo fast and strong variations in the near-wall region, highlighting the non-equilibrium aspect of the layer, which makes the modelling a challenging task. This is in agreement with laser induced fluorescence (LIF) images (Djenidi et al., 2002) of a turbulent boundary layer subjected to a concentrated wall suction. The images revealed that suction stabilizes the near-wall low-speed streaks by reducing their spanwise oscillations. Furthermore, the streaks were observed to stay closer to the wall for a longer extent as compared to the non disturbed boundary layer. Unfortunately, as is always the case with hot-wire measurements, the near-wall data are stained by errors related to inherent difficulties caused by the use of hot-wires in the near-wall region. Thus, the motivation of the present work is to use laser Doppler velocimetry (LDV) to provide more reliable near-wall data than obtained with hot-wire technique. It constitutes an effort to quantify further the effect of suction on the Reynolds stresses and, in that respect, extends the work of Antonia et al. (1995) and Oyewola et al. (2003, 2004).

An estimate of anisotropy is obtained by examining the ratio of the rms of streamwise, wall-normal and spanwise velocities, denoted u, v and w, respectively. The turbulent kinetic energy (k) is also computed and used to further calculate the Reynolds stress anisotropy tensor b_{ij}.

EXPERIMENTAL FACILITY

The experiment is carried out in a constant-head closed circuit vertical water tunnel with a 2 m long square (250mm x 250mm) Perspex test section. One of the working section walls (the door) is used as the testing wall (Figure 1). The boundary layer is tripped with a 4.5 mm high pebbles glued over the wall span at the leading edge of the door. The porous strip (3.25mm thick, 20mm wide and 240mm long, and made of polytetrafuoroethylene with pore sizes in the range 40-80μm) is mounted flush with the door surface at a distance of about 1m downstream of the leading edge of the door. The strip is placed transversally to the streamwise
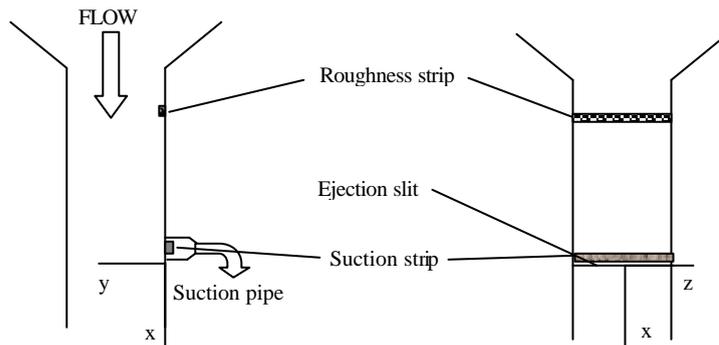

Figure 1. Front (a) and side (b) view of the working section.

direction. The suction rate σ defined as the ratio of the amount of momentum removed and the incoming boundary layer momentum ($\sigma = v_w b/(U_1 \theta_0)$, where v_w is the suction velocity, b the width of the porous strip, U_1 is the freestream velocity and θ_0 the boundary layer momentum thickness at the leading edge of the porous strip) is about 5.9. The freestream velocity U_1 used in this experiment varies from 0.2 to 0.8 m/s (R_{θ_0} = 1000) and the suction rate is 3.3 for the measurements. All the three components of velocity are measured at three different downstream locations, $x/d_0 = 5.5$, 7 and 9, where x is the streamwise coordinate with $x = 0$ corresponding to the trailing edge of the suction strip and d_0 is the boundary layer thickness at the leading edge of the suction strip.

The measurements with and without suction are taken as follow: at each y position, are carried out first without suction then with suction switched on. This ensures that the comparison with and without suction is made at the same y position.

A three-component fibre optic LDV system (4W Ar-Ion) is used with no seeding in forward scatter mode to measure the streamwise, normal-to-the-wall and spanwise velocity components U, V and W; while U and V are measured simultaneously with the same (two color) probe, W is measured separately with the second (color) probe. The measuring volume is about 40 x 40 x 200μm^3, and its longest axis is placed in the transversal direction. Two Enhanced Burst Spectrum Analysers (BSA) are used for processing the photo-multiplier signals. Typical data rates in the outer part of the boundary layer are about 400 Hz, falling off to about 20 Hz close to the wall. In average, about 20,000 samples are collected at each measurement point; this is reduced to about 5,000 close to the wall. Analogue output signals from the BSAs are digitized into a PC and stored for subsequent data reduction and analysis.

RESULTS

Figure 2 shows the profiles of the turbulent kinetic energy, k, with and without suction at x/d_0 = 5.5 and 7. It is important to restate that the comparison with and without suction is made at the same physical distance to the wall. Relative to the no-suction case, k is substantially affected for most of the layer. Note that the peak of k when suction is applied varies substantially with the distance x.
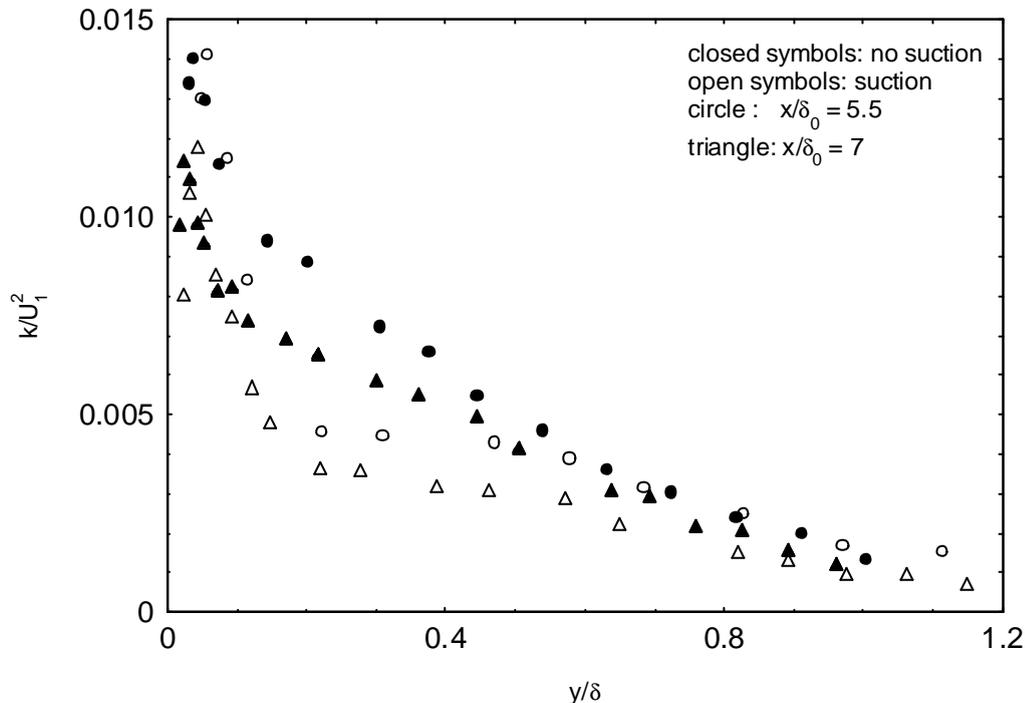

Figure 2: Turbulent kinetic energy with (open symbols) and without
(closed symbols) suction

This is consistent with the hot-wire measurements of Oyewola et al. (2003) which showed that relative to the no suction case and as the downstream distance increases from 0 to 20 d_0, the peak of k first reduces, than overshoots and relaxes to the no perturbed case. Clearly, the perturbed boundary layer, at these downstream positions, is experiencing a departure from the pseudo-equilibrium of the no suction case. This departure is also visible in the structural parameters $<w^2/u^2>$ and $<v^2/u^2>$ shown in the figure 3. Notice the reduction of the parameters in the region $0 < y/d <0.2$ and the increase in the region $0.2 < y/d <0.5$. This suggests that suction interferes with the redistribution of the turbulent kinetic energy among its components. Figure 3, suggests also that the spanwise and normal-to-the-wall fluctuations decreases to the detriment of the longitudinal fluctuations in the region $0 < y/d <0.2$, and increase for $0.2 < y/d <0.5$.
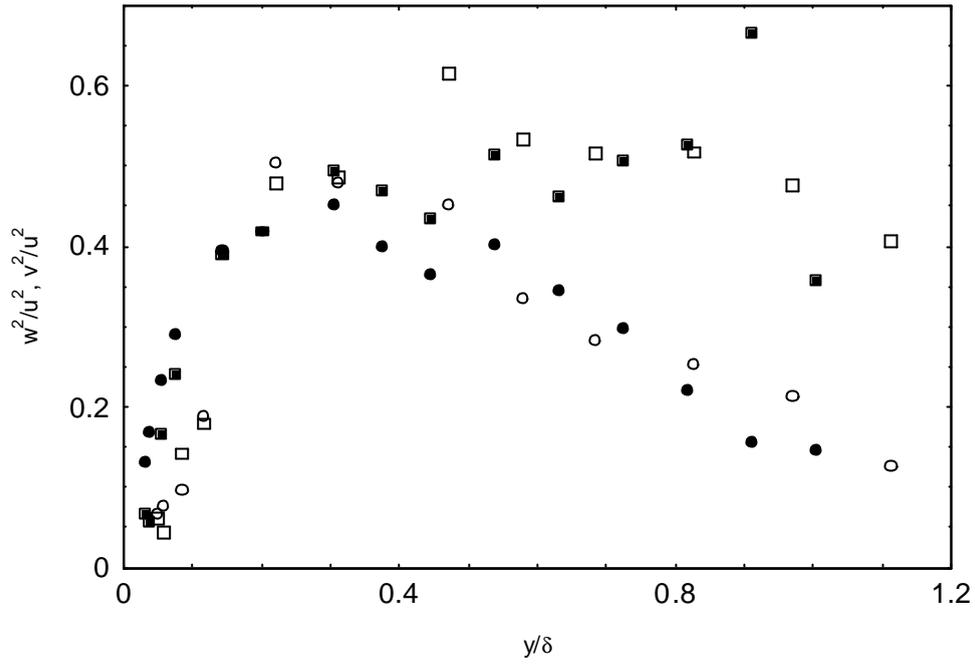
Figure 3: Comparison of w^2/u^2 (circles)and v^2/u^2 (squares) ratios with (open symbols) and without (closed symbols) suction at $x = 5.5d_0$.

The data of Figures 2 and 3 suggest that not only the redistribution of the kinetic energy among its components is altered by suction, but also that the anisotropy of the boundary layer downstream of the suction strip is affected.

To quantify this change, the b_{ij} components are computed and presented in figure 4 for $x/d_0 = 5$ (4a) and 7 (4b)
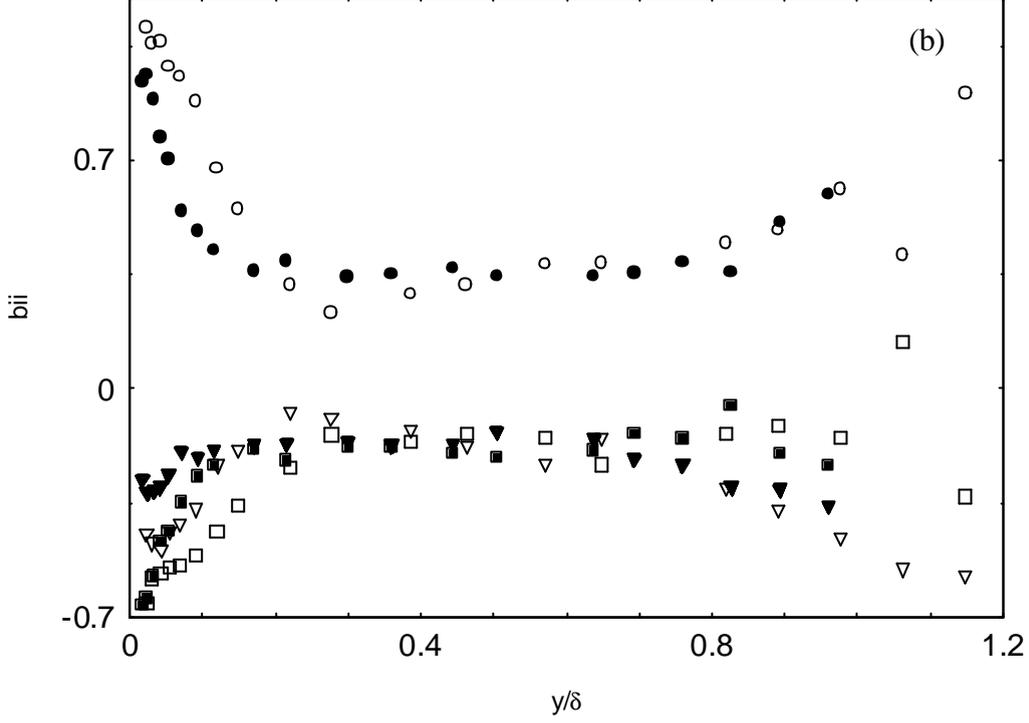
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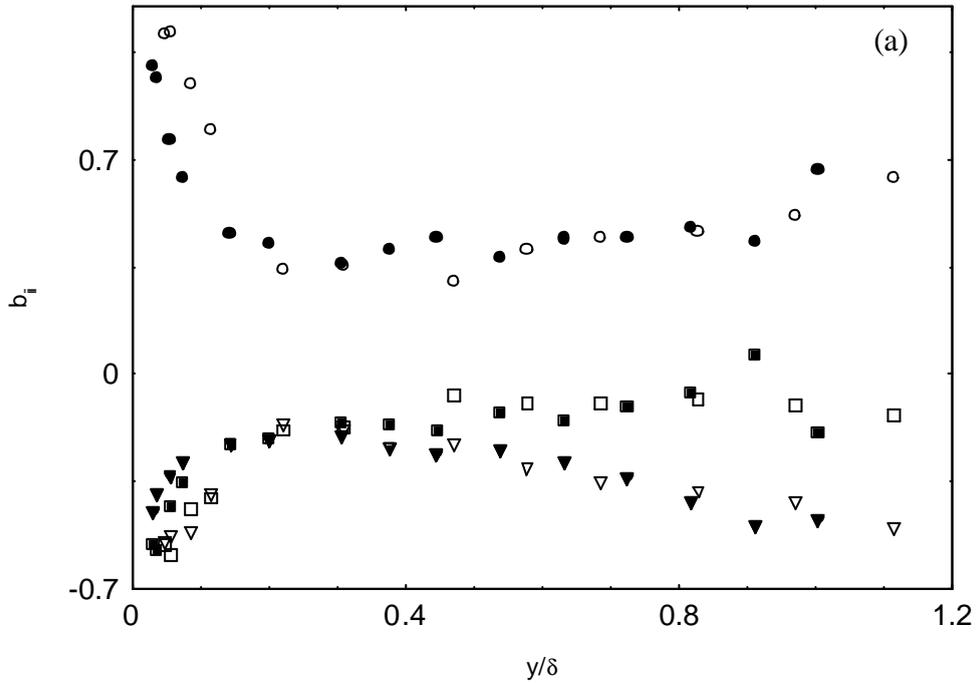
Figure 4: b_{ij} distributions with (open symbols)and without (close symbols) suction at $x/d_0 =$ 5.5 (a) and 7 (b). Circles: b_{11}; Square: b_{22}; Triangles: b_{33}

Relative to the no suction case, all three b_{ii} components are altered by suction in the region $y/d < 0.2$ (i.e in the inner region of the layer), with the alteration least pronounced for b_{22}. The data confirm the comment made earlier that the longitudinal component of the kinetic energy receives more energy than the other two components in the region $0 < y/d < 0.2$. However, energy then flows from u^2 to w^2 in the region $0.2 < y/d < 0.5$ (notice the undershoot and overshoot for b_{11} and b_{33}, respectively, in the region $0.2 < y/d < 0.5$ for $x/d_0 = 7$). It should be noted that one expects this energy transfer process to recover the undisturbed boundary layer case as the flow progresses downstream. The hot-wire data of Oyewola et al (2004) indicated that the transfer of turbulent energy at $x/d_0 = 3.1$ is from u^2 and w^2, then reverses as x/d_0 increases beyond 5. They argued that the increase of w^2 for $x/d_0 < 3$ relative to the other two components of the turbulent kinetic energy is related to an intense downwash behind the suction strip imposed by the downward motion of the flow over the strip.

Clearly, suction affects quite significantly the anisotropy of the boundary layer, particularly in the near-wall region. The effect can further be assessed with the Taylor's anisotropy coefficient on the u^2 and v^2 and w^2 components. The coefficient is defined as

$$K_{a,b} = (a^2 - b^2)/(a^2 + b^2),$$

where a is u or w and b is v or w. For isotropic flows, $K_{u,v}$, $K_{u,w}$ and $K_{w,v}$ are each zero. The coefficient measures the effect of staining on the turbulence. In the present case, the imposition of a strong normal velocity (about 0.5 times the freestream velocity) at the wall, at least in the region near the wall and the downstream of the suction strip, results in a deviation of the flow towards the wall yielding a deformation of the flow as observed in the mean velocity field (not shown here). This deformation in turn results in a straining. Figure 4 shows $K_{u,v}$, $K_{u,w}$ and $K_{w,v}$ with and without suction at $x/d_0 = 7$. Moving away from the wall, the value of these coefficients increases relative to that of the no suction case for $0 < y/d < 0.2$ and reduces for $0.2 < y/d < 0.6$, for $K_{u,v}$, $K_{u,w}$. The nearly zero value of $K_{w,v}$ in the region $0.1 < y/d < 0.6$ reflects the fact that w^2 is underestimated as seen in the w^2 distributions (not shown here). For $y/d > 0.6$, suction seems to affect differently the coefficients: K_{uv} decreases and K_{uw} increases. Since the effect of wall blockage is present in both cases (with and without suctrion) downstream of the strip, one can argue that the variation of the anisotropy observed on figure 5 is mainly due to the extra mean shear induced by suction. This is

consistent with the results of experiments of homogenous turbulence subjected to a mean shear which showed (Gence and Mathieu, 1979) that the shear increases the level of the anisotropy.
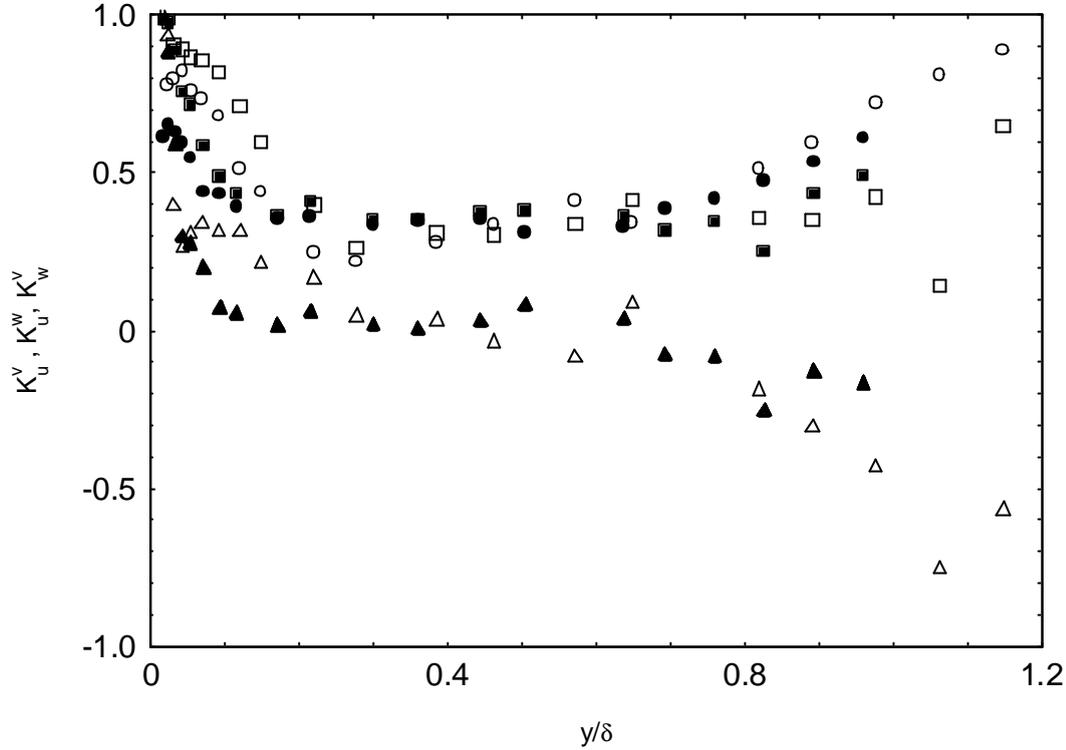

Figure 4: Distributions of K_{uv} (squares), K_{uw} (circles) and K_{wv} (triangles) with (open symbols) and without (close symbols) suction at $x/d_0 = 7$.

CONCLUDING REMARKS

Laser Doppler Velocity measurements are carried out in a turbulent boundary layer subjected to a concentrated wall suction (through a porous strip) over a longitudinal distance (x) of nine times the incoming boundary layer thickness (d_0) behind the suction strip. The data reveal that the redistribution of the turbulent kinetic energy (k) between its components is altered by suction. Relative to the no suction case, the contribution of u^2 to k is stronger in the near wall region ($0 < y/d < 0.2$), while in the region $0.2 < y/d < 0.5$ it contributes less. It is argued that in the former region the turbulent energy flows from v^2 and w^2 to u^2, and from u^2 to w^2 in the latter region. In the region $0.5 < y/d$, the contribution of each component to k is the same as the no suction case. The alteration of the energy transfer between the turbulent kinetic energy components reflects structural changes in the boundary layer.

It is observed that the anisotropy of the Reynolds stresses departs from that of the non disturbed boundary layer. With suction, the anisotropy level in the near wall region appears to be stronger than that of the undisturbed layer. It is argued that the mean shear induced by suction on the flow is responsible for the alteration of the anisotropy. The present LDV data for the anisotropy Reynolds stress tensor corroborate the hot-wire measurements of Oyewola et al (2004), which indicate that the near-wall region state of the layer switches from "cigar-shaped" structures to "pancake-shaped" structures behind the suction strip when suction is applied.

The results presented show that once the boundary layer has been subjected to the local suction, its state departs from that of the pseudo-equilibrium of an unperturbed layer (as it can be seen in the mean velocity profiles, not shown here). While, the boundary layer will eventually recover towards the pseudo-equilibrium some distance downstream of the suction strip, the modelling of the flow in the vicinity of the suction will be difficult. Indeed, the relatively strong streamwise variations of the Reynolds stress in this region precludes

the use of the assumption, often made in the development of turbulence models, that the flow is in pseudo-equilibrium. For example, the return-to-isotropy term in the near wall region will be quite critical for the modelling, and unless the model captures the trend observed on the Taylor's anisotropy coefficients, as seen in figure 5, the effect of suction will not be properly reproduced.

Reference:

Antonia, RA; Zhu, Y; Sokolov, M (1995) Effect of concentrated wall suction on a turbulent boundary layer. *Phys. Fluids* **7**: 2465-2475.

Djenidi, L; Gall, PE; Vincent, A; Antonia, RA (2002) Effect of wall suction on the structure of a turbulent boundary layer. 11th International Symposium on Applications of Laser Techniques in Fluid Mechanics. Paper No. 23.1. Lisbon, Portugal.

Fieldler, H.E. and Fernholz, H.H (1990) On management and control of turbulent shear flows, *Prog. Aerosp. Sci.*, **27**, 305-387.

Gence, J.N and Mathieu, J. (1979) On the application of successive plane strains to a grid-generated turbulence, *J. Fluid Mech.*, **93**, 501-513.

Oyewola, O.; Djenidi, L.; Antonia, RA (2003) Combined influence of the Reynolds number and localised wall suction on a turbulent boundary layer. *Expts in Fluids* **35**: 199-206.

Oyewola, O., Djenidi, L. and Antonia, R.A. (2004) Influence of localised wall suction on the anisotropy of the Reynolds stress tensor in a turbulent boundary layer, *Expts. in Fluids* (to appear)