

# Effect of Wall Suction on the Structure of a Turbulent Boundary Layer

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## ABSTRACT

The present paper reports Laser Doppler Velocimetry (LDV) measurements, and Planar Laser Induced Fluorescence (PLIF) visualisations in a turbulent boundary layer subjected to suction applied through a porous strip. The focus of the study is to investigate the effect suction can have on the boundary layer in the near-wall region, downstream of the suction strip. The mean velocity and fluctuation distributions indicate that when suction is relatively high, pseudo-relaminarisation takes place behind the suction strip. The pseudo-relaminarisation, although not complete, is accompanied by a change in the near-wall structure of the boundary layer. This change is marked by the effect suction has on the low speed streaks, which are associated with the near-wall quasi-streamwise vortices. When suction is applied at relatively high suction rates, the low-speed streaks are less agitated and remain closer to the wall over a longer distance in comparison to what is observed when there is no suction. The effect of suction of the near-wall structure is also reflected in the space correlation coefficient in the spanwise direction. When suction is applied, the correlation coefficient is higher than that when there is no suction, suggesting that the spanwise coherence of the near-wall structure increases. This would suggest that suction would tend to reduce the three-dimensionality features of the near-wall structure of the layer.

A procedure for detecting the low-speed streaks has been developed. The procedure is based on reading an image, filtering it, detecting the edges of streaks and removing the background noise. The procedure is currently tested. Preliminary results indicate that this technique can detect quite reliably the presence of streaks, despite some minor difficulties. Work is being carried out to improve the streak detection. Once the procedure is fully operational and calibrated it will be used to quantify the effect of suction on the streaks, and particularly on their spanwise spacing and the frequency of their bursting.

## INTRODUCTION

The study of how a turbulent boundary layer responds to a disturbance is significant both in terms of fundamental research and engineering applications. One challenging task for engineers is how best to “manage” the turbulent boundary layer in order to achieve a number of desirable outcomes, i.e. reduction in the drag, flow separation delay. In that respect, the use of suction, either through spanwise porous strips or open slots/slits, to achieve certain target such as laminar flow regions, a postponement in flow separation or a delay in transition is of significant interest in industrial applications (Gad-El-Hak, 1989; Pailhas et al., 1991). Moreover, from a fundamental viewpoint, the study of the response of a turbulent boundary layer to sudden application of suction over a relatively short streamwise length provides an opportunity to learn more about the dynamics of the layer (Antonia et al., 1995). For example, the manner in which the near-wall coherent structures respond to suction could allow some insight into the interaction between the wall and the boundary layer. Similarly, interfering with the near-wall structures such as the quasi-streamwise vortices is pertinent to the understanding of the self-sustaining mechanism of wall turbulence.

Recently, Antonia et al. (1995) made hot-wire measurements in a turbulent boundary layer subjected to suction through a spanwise porous strip. Their results clearly indicated that a pseudo-relaminarisation occurs just immediately downstream the suction when the suction rate is sufficiently high. Oyewola et al., (2001) investigated the influence of the Reynolds number on the suction effect. They found that the Reynolds number plays a key factor in the relaminarisation process.

The present paper reports preliminary Laser Doppler Velocimetry (LDV) measurements, and Planar Laser Induced Fluorescence (PLIF) visualisations in a turbulent boundary layer subjected to a suction applied through a porous strip. This work complements that of Antonia et al (1995) and Oyewola et al. (2001). The objective is to investigate the behaviour of the layer downstream of the suction, with particular emphasis on how the low-speed streaks respond to the suction.

## 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 polytetrafluoroethylene with pore sizes in the range 40-80 $\mu$ m) 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 direction. The suction rate ( $\sigma = v_w b / (U_1 \theta_0)$ , where  $v_w$  is the suction velocity,  $b$  the width of the porous strip,  $U_1$  is the freestream velocity and  $\theta_0$  the boundary layer thickness at the leading edge of the porous strip) ranges from 0 to about 5.9. The freestream velocity  $U_1$  used in this experiment varies from 0.2 to 0.8 m/s ( $R_0 = 1090-2130$ ).

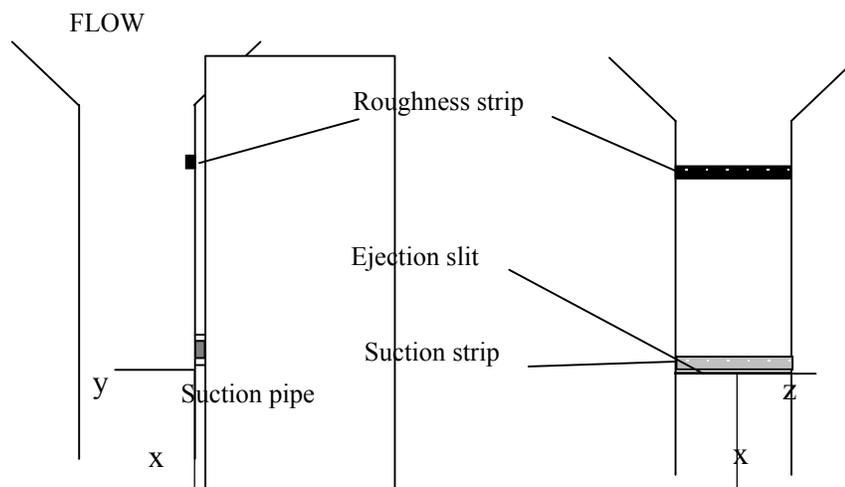


Figure 1. Front view of the working section.

A two-component fibre optic LDV system (4W Ar-Ion) is used with no seeding in forward scatter mode to measure the streamwise and normal-to-the-wall velocity components  $U$  and  $V$  (only results for  $U$  are shown here). The measuring volume is about  $40 \times 40 \times 200 \mu\text{m}^3$ , 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 digitised into a PC and stored for subsequent data reduction and analysis.

The flow visualisation is carried out with the PLIF method, by introducing fluorescein dye into the flow through a transverse slit ( $100 \mu\text{m} \times 160\text{mm}$ ), 8 mm downstream of the suction strip. The dye injection is carefully controlled to avoid any disturbance to the flow. The 4W Argon-Ion laser, used for the LDV, is also used as a light source for the PLIF. The reflection of the laser beam onto a cylindrical mirror causes the expansion of the beam into a planar light sheet, which can be placed either parallel or normal to the wall. The flow visualisation images are recorded via a CCD camera onto video and then digitised through a video card (256 grey levels). The camera resolution is about  $1\text{k} \times 1\text{k}$  pixels, i.e.  $50 \mu\text{m}$  per pixel.

### Results

Figures 2 and 3 show measurements of the streamwise mean velocity and streamwise rms velocity fluctuation at two positions downstream of the suction strip for  $\sigma = 3.4$ . The data are normalized with  $U_\tau$  and  $\nu$  ( $U_\tau$  and  $\nu$  are the friction velocity and kinematic viscosity, respectively). The friction velocity was determined by measuring the velocity gradient in the region  $0 \leq y^+ \leq 5$ ; the uncertainty error associated with this method of estimation of  $U_\tau$  is about  $\pm 5\%$ . For comparison, we have also included the hot-wire data of Oyewola et al. (2001).

Clearly, the LDV data exhibit a similar behaviour to that of the hot wire data. Immediately behind the suction strip, the boundary layer responds quite violently to the suction, as illustrated by the departure of the disturbed profiles from that for  $\sigma = 0$ .

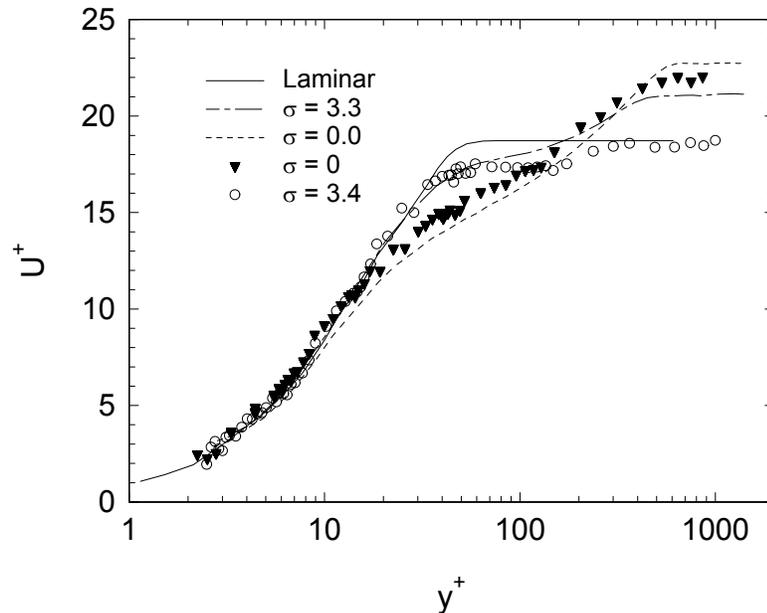


Figure 2: Mean velocity distributions. Symbols : LDV measurements at  $x/\delta_0 = 3.1$ ,  $R_0 = 1090$ . Dashed lines: hot-wire data at  $x/\delta_0 = 3.3$  and  $R_0 = 1400$ . Note that the in the present LDV mean velocity data follow closely the laminar profile in the region  $0 \leq y^+ \leq 30$ . This indicates that a pseudo-relaminarisation is taking place behind the suction strip. The relaminarisation, however, is not complete as it can be inferred from the rms distributions. Indeed while the rms is significantly reduced when suction is applied it is not negligible. The above results suggest that the turbulent boundary layer undergoes structural changes, at least immediately downstream of the suction strip, when sufficiently high suction rates are used. To investigate this, PLIF visualisations of the near-wall region of the layer have been undertaken. Figure 4

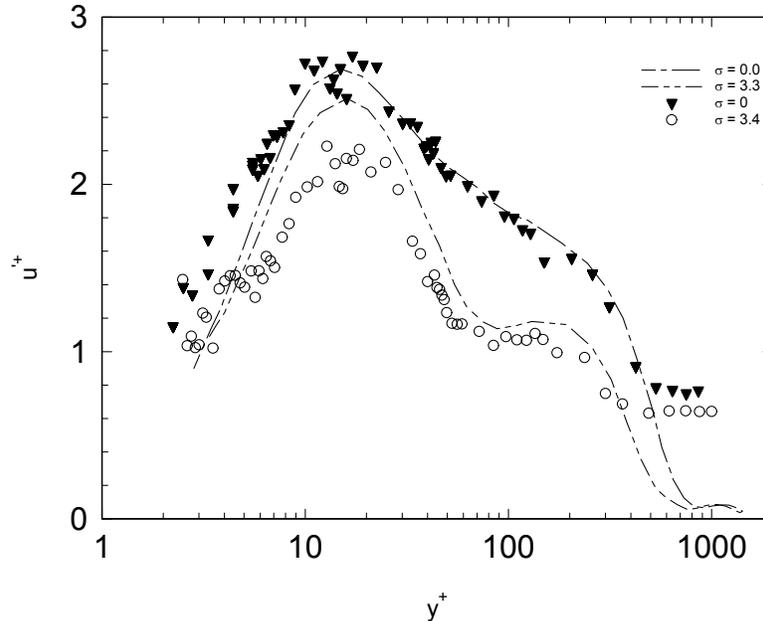


Figure 3: RMS distributions. Symbols, same as in Figure 2.

(view in the  $x$ - $z$  plane,  $x$  and  $z$  are the streamwise and spanwise directions, respectively) is a sample taken from the PLIF visualization. It shows the presence of low-speed streaks downstream of the suction strip. The sequence of images showed vividly that these low-speed streaks become more coherent and less “agitated” when suction is applied, suggesting a more quiescent near-wall flow structure than that when no suction is applied. The visualization showed that the stronger the suction rate is, the quiter is the near-wall flow. When  $\sigma = 5.9$ , the near-wall flow showed little “turbulence” activity, i.e. the flow maintained an almost laminar regime. It was observed that the greater the suction rate, the stronger is the constraint on the streaks. Since these streaks are associated with near-wall quasi-streamwise vortices, their impairing reflects the effect suction has on these vortices. The behaviour of the streaks as suction intensifies may suggest a weakening of the strength of quasi-streamwise vortices as well as an increase in their length. The effect of suction on the length of the low-speed streaks is well

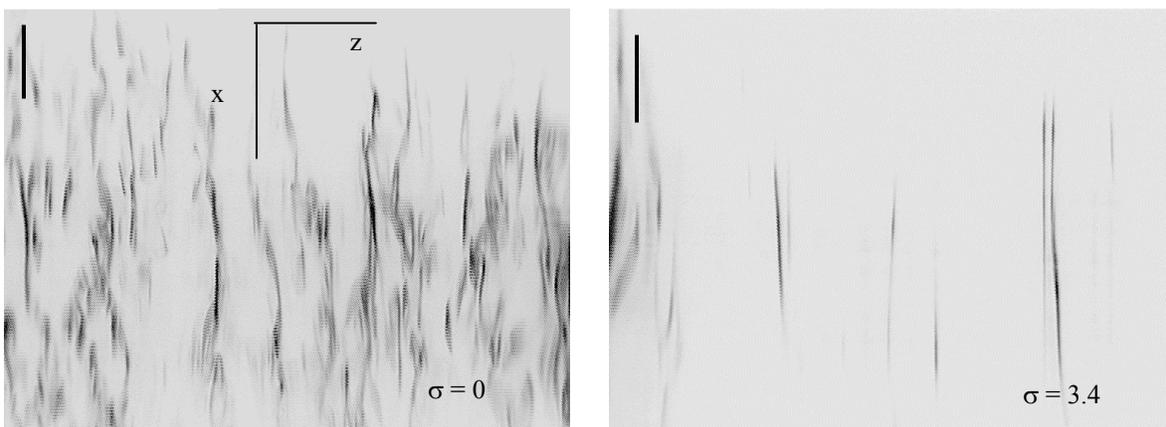


Figure 4. Low-speed streaks. The arrows indicate the flow direction.



Figure 5. Side view of the low-speed streaks. The large arrow indicates the flow direction.

illustrated in Figure 5 which shows a side view ( $x$ - $y$  plane) of the streaks for several values of  $\sigma$ . When  $\sigma = 0$ , the low-speed streaks show the expected general features: elevation of the streaks from the wall at about  $15^\circ$  inclination with the wall, and a sudden “bursting” or ejection at about  $45^\circ$  inclination. When suction is applied with a sufficiently high suction rate, the streaks remain “attached” to the wall over a longer distance before they rise and eventually break out. This explains why in Figure 4 there appear to be fewer streaks when suction is applied: most of the streaks are below the laser sheet. As one may expect with the increase in the longitudinal coherence of the streaks, the frequency of the bursting of the streaks should decrease. Figure 6 shows the frequency of bursting (a bursting was defined as an ejection away from the wall of dye marking

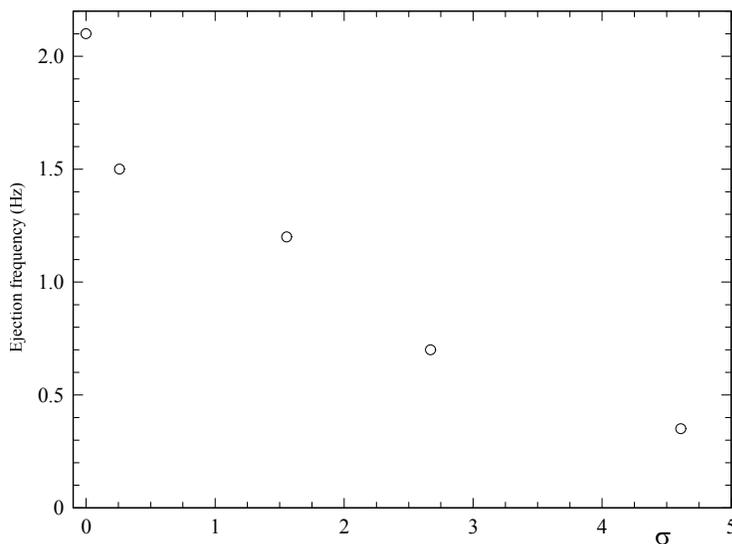


Figure 6. Dependence of the bursting frequency on  $\sigma$

a low-speed streak). When  $\sigma$  increases the frequency of the ejections decreases, which is consistent with figure 5: as the ejections (i.e. bursting) reduce, the low-speed streaks remain longer. The increase of the longitudinal coherence is accompanied by a reduced spanwise agitation, as already seen in figure 4. This reduced agitation may result from a stabilizing effect of suction on the coherent structures near the wall. This can be inferred from the spatial

correlation  $R_{uu}(\Delta z)$  ( $=\langle u(z_0)u(z_0+\Delta z) \rangle / \langle u(z_0)u(z_0) \rangle$ , the bracket  $\langle \cdot \rangle$  represents the time average) shown in Figure 7. The correlation is measured at the distance to the wall corresponding to  $y^+ = 40$  when  $\sigma = 0$ . Note that  $R_{uu}$  should reach the value of one for zero separation. This could not be achieved, as it was difficult to obtain a very accurate positioning of the two measuring volumes at the same point. However, in order to obtain a meaningful comparison between the different cases of  $\sigma$ , the measurements were taken with the three values of  $\sigma$  in turn at a given  $z$  position before moving to the next position. When suction is applied, the values of  $R_{uu}$  are stronger relative to those for  $\sigma = 0$  in the region  $50 < \Delta z^+ < 150$ . Although not clearly visible, the increase of  $R_{uu}$  is stronger as  $\sigma$  increases. The increase of  $R_{uu}$  reflects an increase in the spanwise coherence structures in the near-wall region. This is consistent with the flow visualizations (Figures 4 and 5): As suction is applied the near-wall structures, mainly the quasi-streamwise vortices, as marked by the low-speed streaks, remain close to the wall over a longer distance downstream of the suction with a reduced spanwise agitation. One may argue that Figures 4 and 7 suggest that suction tends to reduce

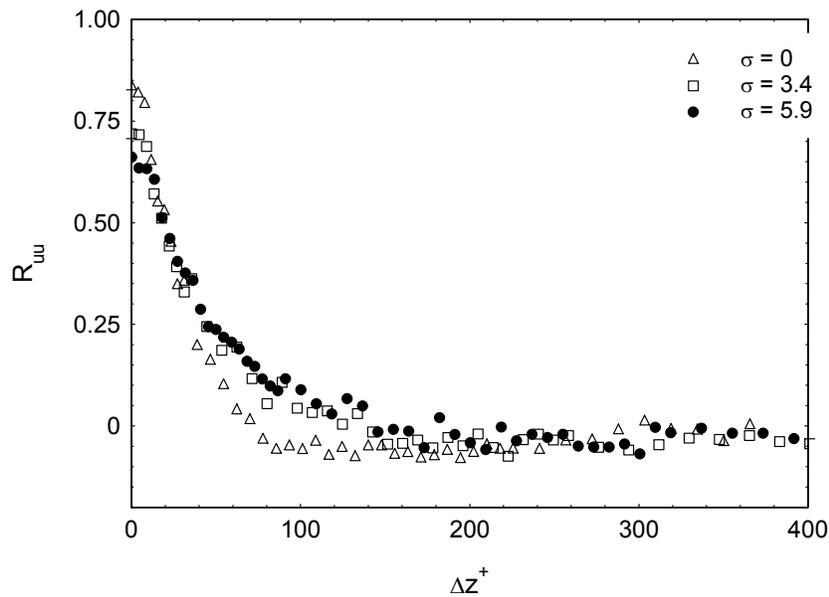


Figure 7. Spatial correlation  $R_{uu}$  in the spanwise direction.

the three-dimensionality features of the near-wall structure of the boundary layer. This argument is consistent with the idea that suction imposes a spanwise constraint on the flow. Clearly further investigation on this and the behaviour of the streaks with suction is required.

Work is currently under way and, to allow a quantification of the effect suction has on the low-speed streaks, a method for detecting these streaks is currently being undertaken using a procedure, which consists in reading an image, filtering it, detecting the edges of the streaks and removing the background noise. Figure 8 shows an example of streak detection. The figure includes the image, the unfiltered intensity profile, the filtered intensity profile and the profile for the detected streaks. The detection is carried out along a straight line, which can be swept across the image, and oriented in any direction. The actual detection of the streaks is based on measuring and comparing the intensity of neighbouring pixels. This technique should allow the assessment of the effect suction has on the spanwise wavelength ( $\lambda$ ) of the low-speed streaks. The procedure is still in the development phase. Note that all streaks are well detected. The major difficulty is related to the recognition of a streak. That is when can the procedure determine objectively whether a peak in the intensity profile represents a streak or not? For example, in Figure 8 it can be seen that the procedure has detected a series of peak in the intensity profile. It is however clear that some of these peaks (some are marked by a small arrow in the figure) do not represent a streak. Procedure to disregard such peaks in the streak detection is currently developed.

A preliminary test of the streak detection procedure is reported in Figure 9, which shows the averaged normalized separation  $\lambda^+$  between the low-speed streaks for a streamwise distance  $2.2 < x/\delta_0 < 3.1$  (about 100 images for each

suction rate were used to calculate the average value of  $\lambda$ ). Images from the sequences used to carry out the detection for each suction rate are also shown. First, the high values of  $\lambda^+$  should be commented on. The value of  $\lambda^+$  for an undisturbed smooth wall turbulent boundary layer is about 100 (see Panton, 1997). Figure 9 shows a value about 200. The difference is likely to be related to the positioning of the laser sheet. Indeed, the value of 100 is for a distance from the wall of about 10 wall units. In the present experiment the laser

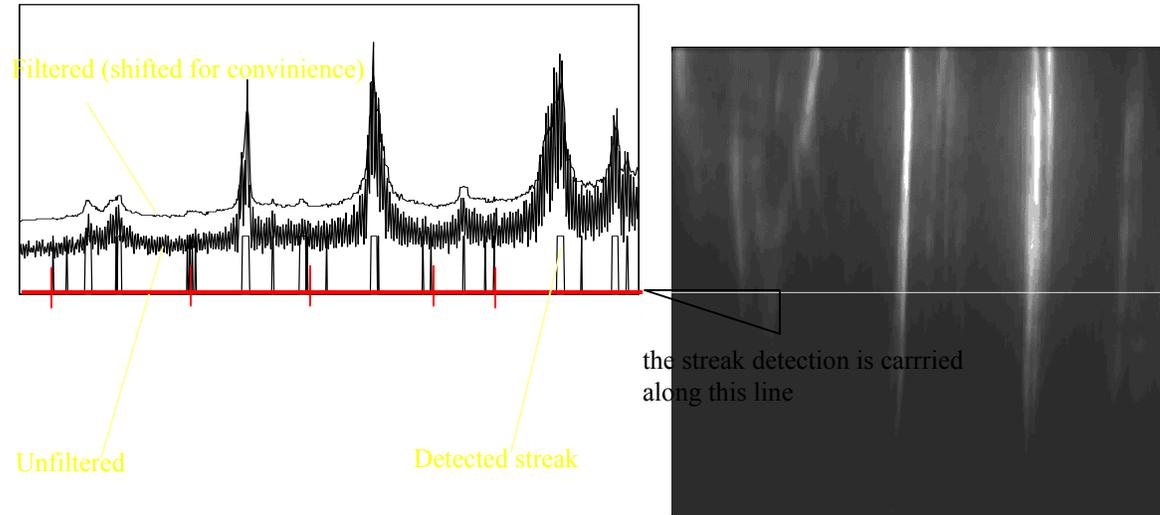


Figure 8. Low-speed streaks detection. The flow is from top to bottom. The detected streaks are represented by the rectangular squares.

sheet is relatively higher than this distance; it is estimated to be at  $y^+ = 70$ . However, since the flow visualization set up does not change (same laser sheet, same distance to the wall, same injection) between the various flow conditions, the comparison between different suction rates should be appropriate. The behaviour of  $\lambda^+$  shows a rather non trivial pattern:  $\lambda^+$  increases to a maximum with  $\sigma$  than reduces as  $\sigma$  keeps increasing. Further work is required to provide a definitive conclusion.

## CONCLUDING DISCUSSION

Laser Doppler Velocimetry (LDV) measurements, and Planar Laser Induced Fluorescence (PLIF) visualisations have been carried out in a turbulent boundary layer subjected to suction applied through a porous strip. The focus of the study is to investigate the effect suction can have on the boundary layer in the near-wall region, downstream of the suction strip. Several values of suction rates,  $\sigma$ , have been used. It was found that for a sufficiently high suction rate, the mean velocity distributions followed that of Blasius in the near wall region, indicating a beginning of a pseudo-relaminarisation process behind the suction strip. The profiles in the log region depart significantly for those for  $\sigma = 0$ . The fluctuating longitudinal velocity distributions also present a significant departure from that for  $\sigma = 0$ . However, the level of the rms suggests that relaminarisation is not complete.

The pseudo-relaminarisation, although not complete, is accompanied by a change in the near-wall structure of the boundary layer. This change is marked by the effect suction has on the low speed streaks, which are associated with the near-wall quasi-streamwise vortices. When suction is applied at relatively high suction rates, the low-speed streaks are less agitated and remain closer to the wall over a longer distance in comparison to what is observed when there is no suction. It is argued that suction tends to reduce the three-dimensionality features of the near-wall structure of the boundary layer. The space correlations coefficient in the spanwise direction supports this argument. Indeed, when suction is applied the correlation coefficient is higher over a longer spanwise distance than that for no suction.

Further work is currently being carried out to quantify the effect suction has on the low-speed streaks. This work uses a procedure for detecting the low-speed streaks, which consists in reading an image, filtering it, detecting the

edges of streaks and removing the background noise. This procedure detected relatively well the presence of a streak. However some minor difficulties are still to be resolved to allow for a complete investigation of the effect of suction on the streaks. Work is currently in progress to resolve such difficulties.

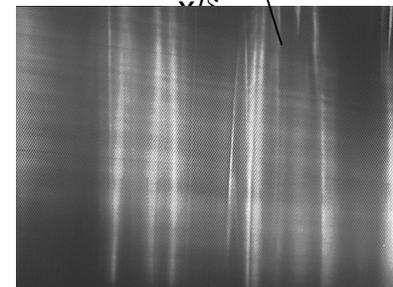
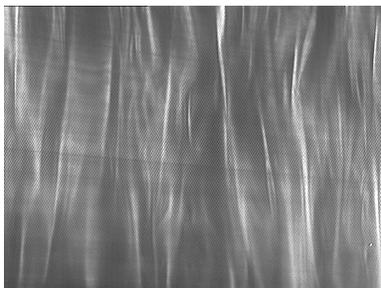
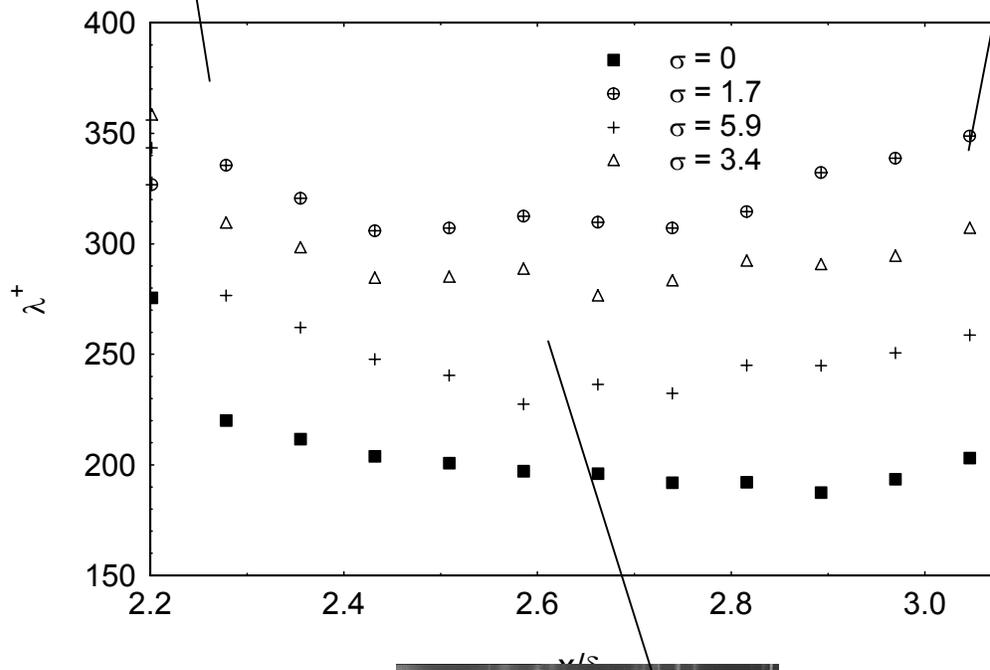


Figure 9. Spanwise separation of the low-speed streaks. The images are taken from the flow visualisation sequences for each case of  $\sigma$ . On the pictures, the flow in from top to bottom.

### References

Antonia, R.A., Zhu, Y. and Sokolov, M., 1995, Effect of Concentrated Wall Suction on a Turbulent Boundary Layer, *Phys. Fluids*, **7**, 2465-2475.

Gad-El-Hak, M., 1989, Flow Control, *Appl. Mech. Rev.*, **42**, 261-293.

Oyewola, O., Djenidi, L. and Antonia R.A., 2001, Effect of Wall Suction on a Turbulent Boundary Layer: Reynolds Number Dependence, In: Proceedings of 14<sup>th</sup> Australasian Fluid Mechanics Conference, Adelaide, 9-14 December, 239-242

Pailhas, G. Cousteix, J, Anselmet, F. and Fulachier, L., 1991, Influence of Suction Through a Slot on a Turbulent Boundary Layer. In: Proceedings of 8<sup>th</sup> Symposium on Turbulent Shear Flow, 18.4.1-18.4.6.

Panton, R.L.(ed.), 1997, Self-sustaining Mechanisms of wall Turbulence, Computational Mechanics Publication.