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LDV Measurements in a Perturbed Turbulent Boundary Layer

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Abstract: The use of the Laser Doppler Velocimetry and Hot-wire measurements techniques to measure the effect of suction on a turbulent boundary layer shows that the boundary layer is undergoing relaminarisation when suction is applied. This is due to suppression of near-wall structure by suction. Quantitatively, there is variability in the two measuring techniques. The variability is within the range of 20%.

Key words: Turbulence, boundary layer, suction, measurements, relaminarisation, velocity

INTRODUCTION

Measuring the effect of changes in boundary conditions in fluid flow is essential in order to quantitatively and qualitatively examine it response. Hot wire measurement has been one of the oldest methods to quantify the fluid flow especially turbulent flow. Antonia *et al.* (1995) used the hot wire to examine the effect of suction on a turbulent boundary layer. They showed that, when the suction rate is sufficiently high, relaminarisation occurred almost immediately downstream of the suction strip. Further downstream, transition occurs followed by a slow return to a fully turbulent state. Furthermore, Oyewola *et al.* (2003) extend the work of Antonia *et al.* (1995) and used hot wire measurement to quantify the combined effect of suction on the turbulent boundary layer. They found that both the suction rate, σ and the momentum thickness Reynolds number, R_θ played important role in the relaminarisation process. They argued that the ratio R_{θ_0}/σ (θ_0 is the momentum thickness of the boundary layer at the leading edge of the porous strip when $\sigma = 0$) should not exceed a (as yet undetermined) critical value if relaminarisation is to occur. Also, Oyewola *et al.* (2004) examined the effect of suction on the anisotropy of the Reynolds stress tensor using hot wire anemometry. They found that the anisotropy of the large scale motion is significantly altered by suction and the degree of anisotropy is increased as the suction rate is increased. However, it is good to examine the respond of the effect of suction on a turbulent boundary layer using other measuring technique in order to ascertain qualitatively and quantitatively what has already been obtained using hot-wire measurements by Antonia *et al.* (1995) and Oyewola *et al.* (2003).

The aim of the present short communication is to examine the effect of suction on a turbulent boundary through the measurements of mean velocity and Reynolds stresses using Laser Doppler Velocimetry (LDV). This measuring technique is being used because it is one of the latest techniques to measure fluid flow because of it accuracy and less time required. The results obtained are compared with the hot-wire measurements of Oyewola *et al.* (2003).

MEASUREMENT DETAILS

The experiments were carried out in a closed circuit constant head vertical water tunnel as shown in Fig. 1. The vertical 2 m high working section (250 mm square cross section) is made of 20 mm thick clear Perspex. One of the walls of the working section, which is removable, was used as the testing smooth wall. A roughness strip, made up of 4.5 mm high pebbles glued onto a 30 mm wide Perspex strip and recessed into a groove about 100 mm downstream from the exit of the contraction and was used to trip the boundary layer. Tests showed that the boundary layer was fully developed well upstream of the working section before suction strip location. A 3.25 mm thick porous strip of stream-wise length 40 mm and made of sintered bronze with pore sizes in the range 40-80 μm was mounted flush with the working section floor and is located about 1 m downstream of the leading edge of the testing wall. Suction was then applied through a valve placed behind the suction strip connected to a flow meter (maximum flow rate 2 $m^3 s^{-1}$) and was driven by the static pressure. The free stream turbulence intensity is less than 2% for the present U_1 values. The pressure gradient was checked by measuring U_1 at several axial locations and found to be negligibly small. Measurements were made at $R_{\theta_0} = 750$ and for $\sigma = 0$ and 3.3. Because of poor near-wall measurements, the U_τ used was obtained by assumed an existent of a power law. These values are likely to be under or over estimated especially if the boundary layer is disturbed by suction.

For the measurements, a three-component fibre optic LDV system (5 W Ar-Ion) was used in forward scatter

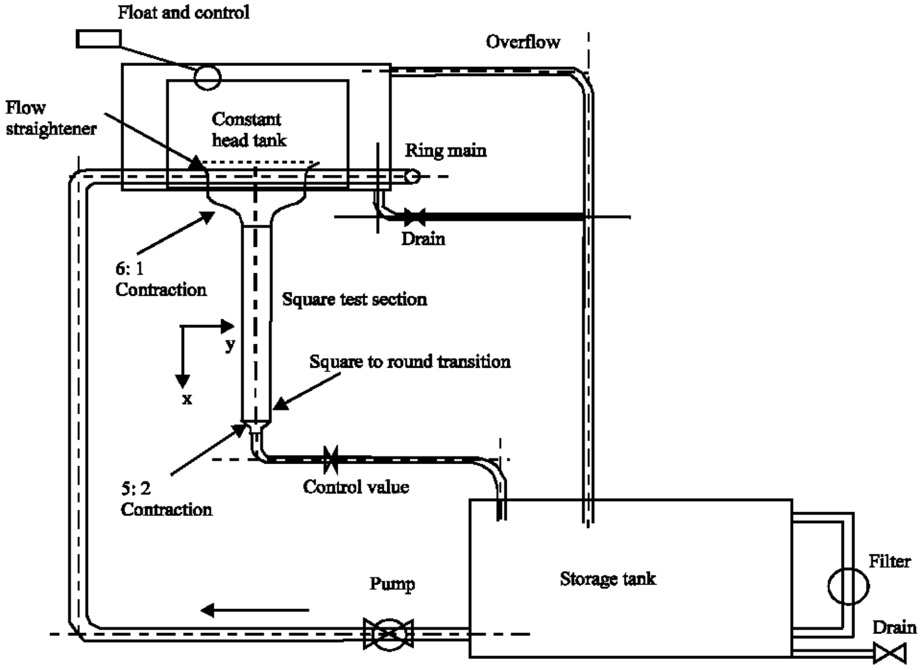

Fig. 1: Schematic arrangement of the water tunnel

mode. Only two-component measurements for u-v were performed. Since refractive index effects are wavelength dependent, the two pairs of beams with the closest wavelength (in this case, blue and violent with wavelengths 488 and 476.5 nm, respectively) were used. The measuring volumes (0.04×0.5 mm for the blue beams and 0.04×0.9 mm for the violet beams) had their largest dimension oriented along the spanwise direction in order to optimize the spatial resolution (in the range 0.16 to 0.8 wall units) in the wall-normal direction. In this configuration, the beam closest to the wall (used for the wall-normal component) was centered using a pair of prisms and the probe was slightly tilted ($\approx 2^\circ$) with respect to the z-direction in order to obtain measurements very close to the wall. The probe was manually traversed in the longitudinal and normal directions.

Enhanced Burst Spectrum Analyzers (BSA) were used for processing the photo multiplier signals. The two-component measurements were made in the coincidence mode, except very closed to the wall where the data rates fall off quite steeply. In the coincidence mode, the two BSAs process the LDV signals only when the two signals are within the set coincidence time interval, allowing a more reliable measurement of the Reynolds shear stress-$\langle uv \rangle$. Very close to the wall, operating in coincidence mode was not feasible because of the very low data rates. In this case, in order to improve the data rates, the BSAs were operated in the private mode whereby the signals are processed independently. Typical data rates in the outer part of the boundary layer were about 300 Hz, falling off to about 70 Hz very close to the wall. In the outer part of the boundary layer, 20,000 samples were collected at each measurement point and this was reduced to 6,000 samples very close to the wall.

RESULTS AND DISCUSSION

Figure 2 show the mean velocity distributions for the LDV and the hot-wire measurements. Also shown in the figure is the DNS data of Spalart (1988) at $R_\theta = 1400$. The no-suction LDV data show reasonable agreement with the single wire and DNS data, taking into account the different in the Reynolds numbers. The profiles collapsed well in the region $y^+ \leq 10$ and the suction data show expected departure from the zero-suction data in the other part of the boundary layer. Although, the LDV data show a greater departure relative to no-suction than the hot-wire data, the agreement between the two measurements techniques corroborates the conclusions made by Oyewola *et al.* (2003) that the boundary layer is undergoing relaminarisation process. This is not surprising, since relaminarisation of the boundary layer do occur for appropriate Reynolds number and suction rate. The breaking down of Log-Law and outer regions in the present distributions signify that relaminarisation is occurred. The departure in the outer region of the boundary layer indicates a reduction in the outer length scale of the layer, which, eventually lead to a decrease in the local Reynolds number.

Figure 3 shows hot-wire and LDV measurements of the Reynolds stresses. Also show is the Reynolds shear stress of the two measurements techniques for $R_{\theta_0} = 750$ and for suction rate $\sigma = 0, 3.3$. While the measurements of u'^+ show a good agreement in the region away from the wall, the quality of agreement at the near-wall region is poorer. Also, the agreement between the measurements techniques for v'^+ and $\langle u^+v^+\rangle$ is poorer in the near-wall region of the boundary layer. While the hot-wire data of $\langle u^+v^+\rangle$ is lower than those of LDV data for both suction and non-suction cases, they are however in agreement qualitatively. This is not surprising considering the inadequacy of the hot cross-wire measurements in the region near the wall (Legg *et al.* 1984, Perry *et al.* 1987) and this is likely to cause significant turbulence attenuation. Meanwhile, the significant drop in the data rate in the LDV measurements in the near-wall region also renders the accuracy of the data to be in question. Therefore, data in the region $y^+ \leq 10$ should be discarded especially for v'^+ and $\langle u^+v^+\rangle$. Interestingly, the two measuring techniques show that there is a difference between the disturbed and undisturbed boundary layer. For example, in all the distributions, the suction data departs from their corresponding no-suction case throughout the boundary layer. The result suggests a structural change in the boundary layer due to the weakening of the structures in the near wall region.

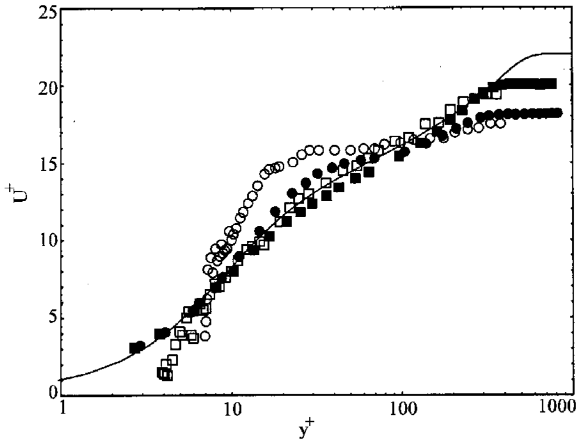

Fig. 2: Mean velocity profile. Open symbol: Water tunnel; Closed Symbol: Wind tunnel. ■, □: $\sigma = 0$; ●, ○: $\sigma = 3.3$; -: Spalart

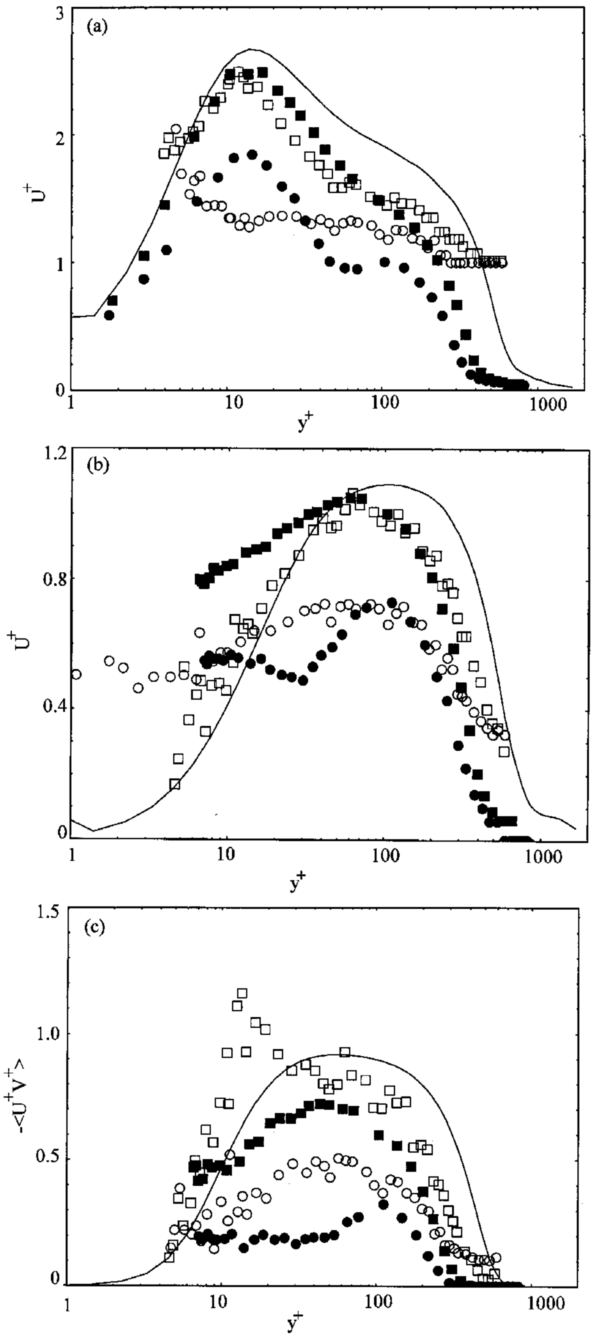

Fig. 3: Variations of (a) u'^+; (b) v'^+; (c) $-u^+v^+$. All symbols are as in Fig. 2.

While the changes in u'^+ and v'^+ may suggests a weakening of the streamwise vortices, which contributes to the turbulent production, the changes in $\langle u^+v^+\rangle$ further indicate a change in the momentum transfer between the two boundary layers. The variability in the two measuring techniques is less than 10% for no suction and about 20% for suction case. It is possible that either hot wire or LDV is over or under estimated especially in the near-wall region. Nevertheless, the two measuring techniques proved useful in measuring a change in boundary condition in a fluid flow. The present measurements using

LDV qualitatively in support of the previous finding of Oyewola *et al*. (2003) and Antonia *et al*. (1995). It is therefore would be a useful measuring technique than hot-wire measurement in measuring the effect of changes in boundary conditions because hot-wire measurements are time consuming. However, for future work, the data rate should be increased and this will possibly improve the accuracy of LDV measurements.

CONCLUSIONS

Measurements of the LDV and hot wire have been examined in a turbulent boundary layer subjected to a concentrated suction. The result indicates a change in the boundary layer when suction is applied and suggested that the boundary layer is undergoing relaminarisation. The change in the transverse velocity and Reynolds shear stress indicates a weakening of the vortical structures of the boundary layer. The two measuring techniques showed a relative consistency without suction than with suction. The variability is in the range of 20%.

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