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# TURBULENT BOUNDARY LAYER OVER TRANSVERSE SQUARE CAVITIES

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## ABSTRACT

Laser Induced Fluorescence (LIF) visualizations and Laser Doppler Velocimetry (LDA) measurements have been made in a turbulent boundry layer over a wall made up to two-dimensional square cavities placed transversally to the flow direction. The visualizations indicate frequent though random outflows of fluid from the cavities as well as inflows into the cavities. There is strong evidence that the outflows are associated with the passage of near-wall quasi-streamwise vortices which are similar to those found in a smooth wall turbulent boundary layer. Self-preservation appears to be more closely satisfied than on a smooth wall. It is however conjectured, on the basis of the LDV measurements, that **exact** self-preservation cannot be satisfied. Relative to a smooth wall layer, there is a discernible increase in the magnitudes of all the Reynolds stresses. A local maximum in the Reynolds shear stress occurs in each shear layer above a cavity.

## INTRODUCTION

The interest in the surface (usually referred to as a d-type roughness; Perry et al., 1969), characterized by spanwise two-dimensional square grooves ($h = w_c = 5$ mm, $h$ and $w_c$ are the depth and width of a groove) regularly spaced, one groove width apart in the streamwise direction, stems from the possibility that the boundary layer may be exactly self-preserving, (i.e. only one velocity scale and one length scale are needed to describe the behaviour of turbulence everywhere in the flow) while the turbulence structure is not too different from a smooth wall boundary layer (for example, low-speed streaks are observed on this rough wall, Ching et al., 1995). This particular feature can be exploited to improve our knowledge of the turbulence production mechanism in near-wall turbulent flows. From a methodological viewpoint, it is attractive to study a flow with many similarities to a turbulent boundary layer on a smooth wall, but with some important differences, for example, an apparently improved quality of self-preservation. The present data significantly complement the work of Djenidi et al. (1994) and the flow visualizations of Ching et al. (1995) for the same flow conditions. Despite the relatively large amount of experimental data already available for such a surface, conclusive near-wall data are still lacking. This is mainly due to the fact that hot wire measurements are not reliable in the near-wall region. The use of LDV should help in this respect while LIF should provide important visual information on the near-wall events.

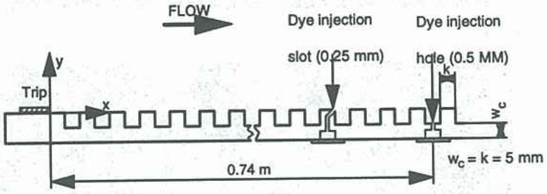

Figure 1: Rough wall geometry.

## EXPERIMENTAL SET-UP

The experiment is carried out in a closed circuit constant head vertical water tunnel. The vertical 2 m high working section (250 mm square) is made of 20 mm thick clear perspex and one of the working section walls is used as the rough wall (Figure 1). A three-component fibre optic LDV system (Dantec 5W Ar-ion), consisting of two probes, is utilised in forward scatter mode. The photo-multiplier signals are processed with two Enhanced Burst Spectrum Analysers (BSA). The flow was seeded with iriodin silver particles (about 2 $\mu$m in size) and the typical data rate in the outer part of the flow is about 1500 Hz; it is about 50 Hz in the very near-wall region ($y < 0.75$ mm). The measurements are carried out at a Reynolds number, $R_\theta$, ranging from 900 to 2300 ($\theta$ is the momentum thickness).

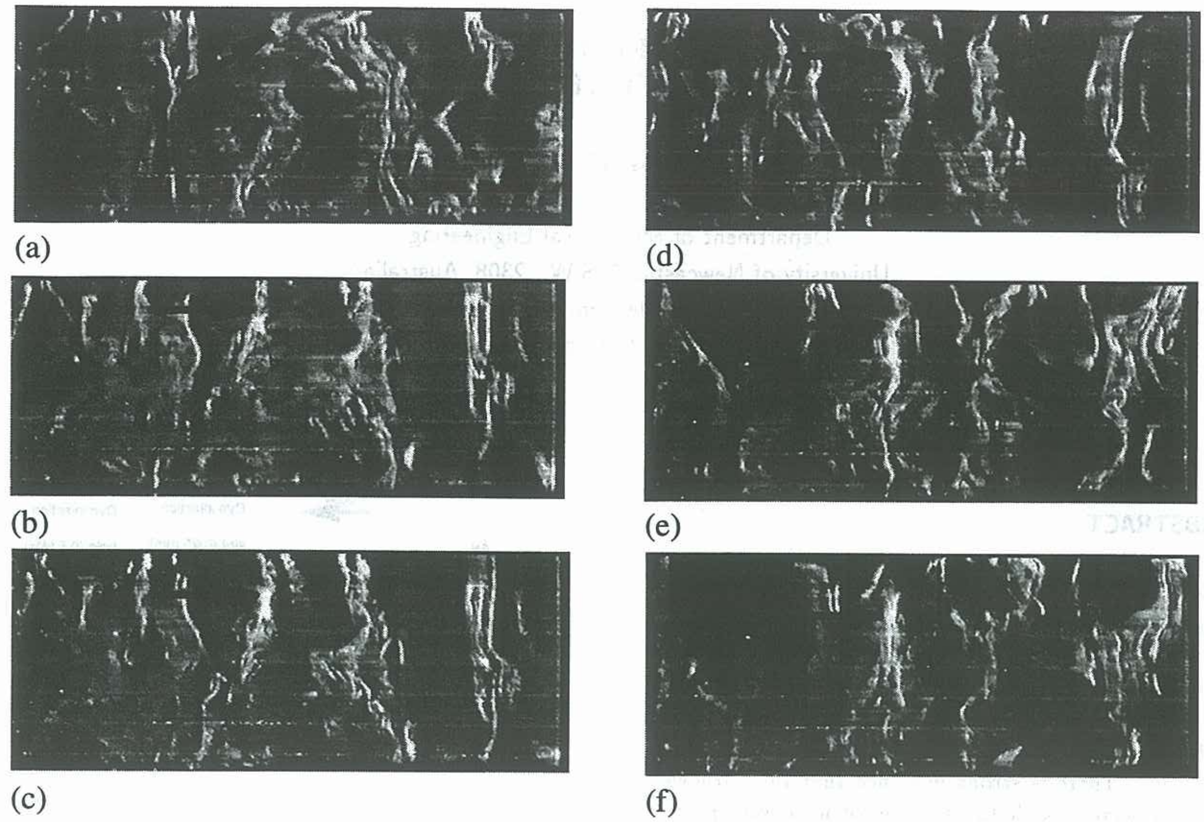

Figure 2: Views in the $x - z$ plane showing an outflow (marked by the arrows) triggered by a low speed streak. In (a), the arrow marks the dye injection hole location.

The LIF visualizations were performed at $R_\theta = 1100$. A sodium fluorescein (2 mg/litre of water), with light absorption and emission wavelength of 510 nm and 540 nm respectively, was injected through a spanwise slot; also a solution of rhodamine was injected through a hole into a cavity (see Figure 1). The dyes were illuminated using a 0.5 mm thick laser light sheet, a CCD video camera was used to record the sequences of flows.

## RESULTS

LIF clearly revealed the presence of low-speed streaks whose appearance and break-up are similar to what has been observed on a smooth wall. The visualizations also indicated frequent though random occurrences of three types of events : (i) outflows from the cavities into the overlying flow; (ii) inflows into the cavities; and (iii) periods where the overlying flow skims over the cavities with no significant exchange of fluid. It is found that the outflows are closely associated with the passage of low-speed streaks (Figure 2). If the low-speed streaks are formed by quasi-streamwise vortices, it is plausible that these vortices also trigger the outflows. Figure 2 shows that fluid is first pumped out from the cavity and then convected along the streamwise direction with the low-speed streaks. Note the rather narrow spanwise dimension of the outflow. Visualization (not shown here) using two laser sheets parallel to each other in the $(x, y)$ plane and separated by a spanwise distance of $0.2\delta$, revealed that an outflow has a spanwise distance of order 100 wall units ($\simeq 0.15\delta$). This is consistent with outflows triggered by pressure fluctuations associated with the near-wall quasi-streamwise vortices.

The conditions for which self-preservation can be achieved were set out by Rotta (1962) : both $U_\tau/U_1$ and $d\delta/dx$ should be independent of $x$ ($U_\tau$, $U_1$, $\delta$ and $x$ represent the friction velocity, freestream velocity, boundary layer thickness and streamwise direction respectively). The present LDV measurements (Figure 3) indicate that these requirements are reasonably well satisfied. Also the mean velocity (not shown here) and Reynolds stress distributions (Figure 4) support this argument. Since $U_\tau$ receives contributions from both viscous and form drag, self-preservation requires that each contribution is constant; alternatively, their sum should be constant. For the present flow, it was found that although the viscous drag is smaller than the form drag, it is not negligible. Since the viscous drag should increase with $x$ (as $\delta$ increases with $x$) one expects that $dU_\tau/dx < 0$. Accordingly, self-preservation can

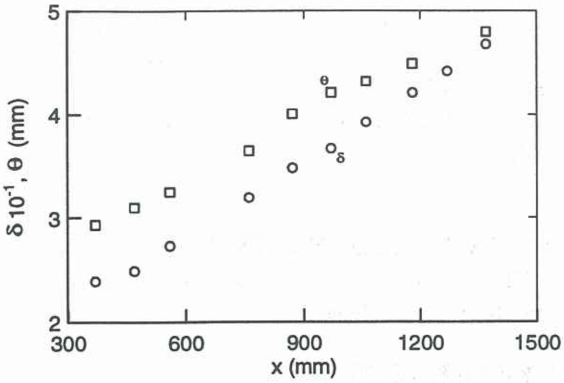

Figure 3: Streamwise distributions of $\delta$ (○) and $\theta$ (□) at $R_\theta = 2100$.

never be satisfied exactly, although $dU_\tau/dx$ should, in general, be smaller for a rough wall than a smooth wall layer. A physical argument, at least for the present rough wall, that may explain this trend is the possibility that $\overline{uv}$ is maintained more effectively over the present surface than on a smooth wall since there is a natural reservoir of low momentum fluid trapped within the cavities. This would facilitate the exchange of momentum between the cavities and the overlying stream which in turn would help maintain a higher turbulent energy production rate/dissipation rate ratio than for a smooth wall. This argument should also apply to other rough surfaces for which the form drag is larger than the viscous drag.

An interesting result revealed by the LDV data is the local maximum in the $-\overline{uv}$ distribution in the vicinity of the surface which is found to be consistent with the equation of motion (Djenidi et al., 1998) : the local maximum occurs at about the same location as that of the inflection point ($\partial^2 U/\partial y^2 = 0$) in the $\overline{U}$ distribution; note that this feature cannot be detected with the use of hot wires. This maximum indicates a strong correlation between $u$ and $v$, underlying the presence of strong coherent events. This is consistent with the frequent though random occurrence of outflows and inflows. This supports the argument that outflows play an important role in enhancing the production/maintenance of turbulent energy in the present rough wall layer. The low momentum fluid trapped in the grooves and released during the outflows provides an input of turbulent energy into the layer. While this process occurs randomly in time, it has a period in the streamwise direction of $2w$; the outflows as well as the inflows invariably occur in the downstream part of each cavity. One can argue that the outflows provide the right level of energy transfer into the flow to ensure energy equilibrium which in turn ensures an improved self-preservation. A consequence of the outflows is an increase in all the Reynolds stresses, relative to a smooth wall — the smooth wall data are those of Erm (1988). The magnitudes of the normalized Reynolds stresses, and particularly $-\overline{uv}$, require some comment. The increase occurs over a large portion of the boundary layer thickness. Also, while $u'$ is increased by about 10%, $v'$ and $-\overline{uv}/U_\tau^2$ are increased by about 30% each. This indicates that $v'$ is more sensitive to the change in the wall condition than $u'$. The local maximum in $\overline{uv}/U_\tau^2$ in the region $0.1 \le y/\delta \le 0.2$ exceeds 1 by as much as 20%. A value of 0.022 m/s deduced by a momentum integral was used for $U_\tau$ (Djenidi et al., 1998). It is about 13% smaller than $(-\overline{uv})^{1/2}_{max}$. Clearly, using $(-\overline{uv})^{1/2}_{max}$ to normalize the Reynolds stresses would reduce their magnitude (the normalized $-\overline{uv}_{max}$ would then be forced to equal 1). It should be pointed out that for the same nominal free

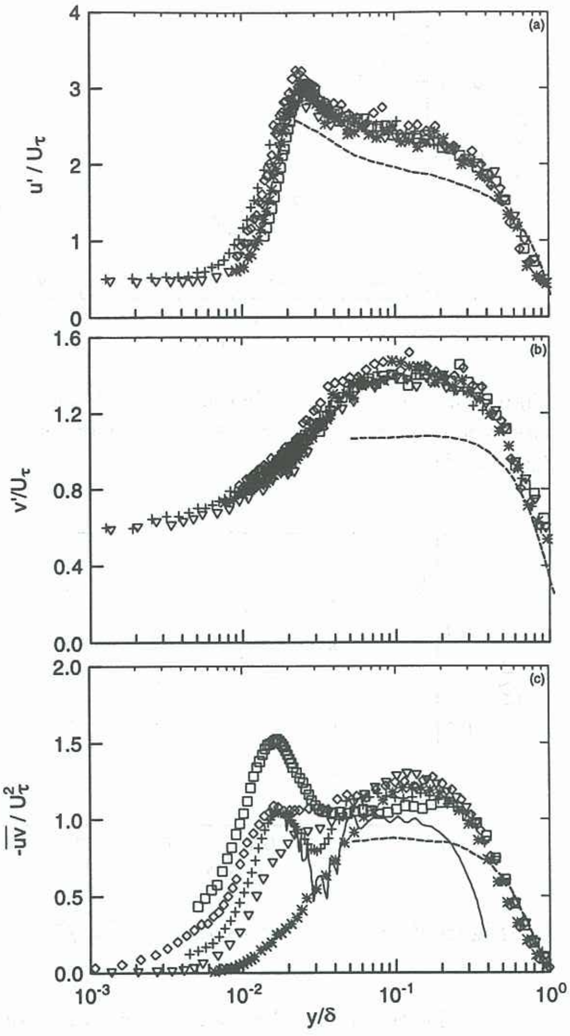

Figure 4: Reynolds stress distributions of (a) $u'/U_\tau$, (b) $v'/U_\tau$, (c) $-\overline{uv}/U_\tau^2$. $*$, 970 mm; $+$, 1060 mm; $\triangledown$, 1180 mm; □, 1270 mm; ◇, 1370 mm; dashed line, Erm (1988) $R_\theta \simeq 2800$. In (c), the solid line represents $-\overline{uv}$ calculated with the equations of motion (see Djenidi et al., 1998).

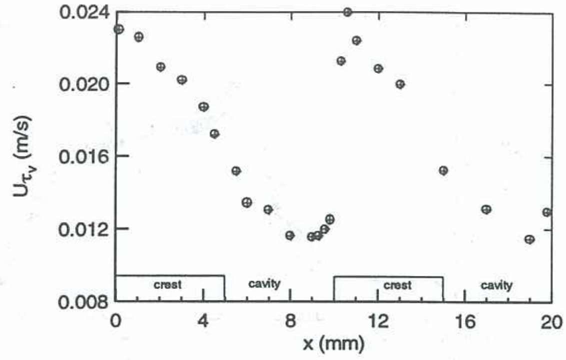

Figure 5: Streamwise distribution of the friction velocity over a distance of two wavelengths ($x/w = 4$).

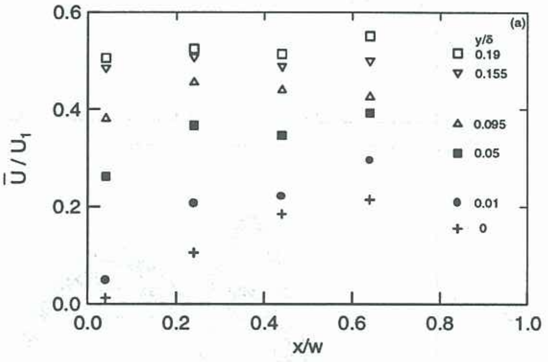

Figure 6: Streamwise variations of $\overline{U}/U_1$.

stream velocity, all the Reynolds stresses are larger than on the smooth wall, as is $R_\theta$.

Figure 5 shows the longitudinal distribution of $U_{\tau_v}$ over a distance of two wavelengths (the subscript $v$ indicates that it is the viscous contribution only which is measured). $U_{\tau_v}$ was estimated by measuring the mean velocity gradient over the crest plane and along a fictitious plane at the top of the cavities. The waviness of the $U_{\tau_v}$ distribution reflects a distortion in the mean velocity streamlines which is illustrated in Figure 6. The waviness is reminiscent of that observed on a wavy wall (e.g. De Angelis et al., 1997) and suggests that the surface imposes a periodic streamwise effect on the wall, at least in the near-wall region.

## CONCLUSION

LIF visualizations and LDV measurements were made in a turbulent boundary layer over two-dimensional square cavities placed transversely to the flow and spaced one cavity apart in the $x$ direction. The visualizations revealed that outflows from the cavities into the overlying flow take place randomly and are associated with the passage of near-wall quasi-streamwise vortices, similar to those found in a smooth wall turbulent boundary layer. The outflows would play a role in the production/maintenance of $-\overline{uv}$, which in turn enhances self-preservation. The latter appears to be more closely satisfied than in a smooth wall layer. However, the LDV measurements indicate that self-preservation cannot be satisfied exactly.

## ACKNOWLEDGEMENTS

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## REFERENCES

CHING, C. Y., ELAVARASAN R. and ANTONIA, R. A. 1995. Visualization of near-wall region in a turbulent boundary layer over a d-type roughness, in J. Crowder (eds.) *Flow Visualization VII*, New York, Begell House Inc., 398-403.

DE ANGELIS, V., LOMBARDI, P. and BANERJEE, S. 1997. Direct numerical simulation of turbulent flow over a wavy wall, *Phys. Fluids*, **9**, 2429-2442.

DJENIDI, L., ANSELMET, F. and ANTONIA, R. A. 1994. LDA measurements in a turbulent boundary layer over a d-type rough wall, *Expts. in Fluids*, **16**, 323-329.

DJENIDI, L., ELAVARASAN, R. and ANTONIA, R. A. 1998. Turbulent boundary layer over transverse square cavities, *J. Fluid Mech.* (submitted)

ERM, L. P. 1988. Low Reynolds number turbulent boundary layers, Ph.D. Thesis, University of Melbourne.

PERRY, A. E., SCHOFIELD, W. H. and JOUBERT, P. N. 1969. Rough wall turbulent boundary layer, *J. Fluid Mech.*, **37**, 383-413.

ROTTA, J. C. 1962. Turbulent boundary layer in incompressible flow, in A. Ferrie, D. Kucheman and L. H. G. Stone (eds.) *Progress in Aeronautical Science*, Oxford, Pergamon Press, 1-220.