The Response of a Turbulent Boundary Layer to Injection through a Porous Strip

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ABSTRACT

The effect of localized surface injection in a fully developed turbulent boundary layer was studied using hot wire techniques. Air was injected through a porous strip with a streamwise extent of about 3δ. As the flow recovered downstream from the perturbed boundary condition, a triple layer structure developed. Near the wall the flow quickly returned to standard flat plate conditions and no effetcs of the blowing could be detected in the outer layer over the downstream distance covered by the measurements ($\approx 23\delta$). In the intermediate layer considerable increases in all the turbulent stresses were found. However, the ratio between the stresses were found to remain the same as for the unperturbed layer, indicating that the flow structure was not affected. This was confirmed by the spectral energy distributions which were not changed. Therefore the intercomponental and spectral energy transfer appears to be sufficiently quick to account for the changes caused by the injection. Significant changes were however found in the production and dissipation of kinetic energy. These changes were compensated by modified diffusion rates.

INTRODUCTION

Turbulent boundary layers with blowing are found in a great variety of practical applications, e.g. cooling of turbine blades and combustion chambers, chemical apparatus, drying processes, special types of high efficiency heat exchangers and boundary layer control. Special attention has been paid to boundary layers developing downstream of a sudden injection through a porous surface strip, due to the applications for turbine blade cooling where transpiration through the entire turbine blade surface at present seems unrealistic. Considerable academic interest is connected to this subject, since the surface blowing radically alters the flow characteristics above the porous strip and this perturbation is felt downstream for a very long distance. Thus reliable experimental data for such flows may provide a good test case for numerical simulations. The reported experiment was undertaken to provide experimental data on mean and turbulent velocities to form a basis for such calculations, as well as trying to provide information on the changes in the turbulent structures caused by surface blowing over a limited streamwise distance.

EXPERIMENTAL DETAILS

The experiments were conducted in an open return wind tunnel, specially designed and manufactured for the present study. The boundary layer investigated developed on the polished aluminium false floor of the working section which had a cross section of 0.46×0.46 m. The boundary layer was tripped at the leading edge by two sets of tripping devices consisting of a 1 mm diameter rod followed by a 5 cm long strip of #40 grit sand paper. The free stream turbulence was less than 0.5 %. The blowing section was installed 2.35 m downstream from the leading edge and consisted of a 0.12 m long porous strip spanning the entire width of the test section. The strip was made of sintered stainless steel with an average hole diameter of 150 μm. Downstream of the blowing strip there was 1 m of smooth wall. Measurements were performed along the centre line at one station half way down the blowing strip and at six stations downstream of the blowing section. Data was obtained for four blowing rates, $F = V_w/U_e \approx 0$, 0.003, 0.006 and 0.009. Measurements were also performed at one station upstream of the strip to determine the characteristics of the incoming flow, which was found to comply with the requirements of fully developed flat plate boundry layers. The roof of the working section was carefully adjusted to provide zero pressure gradient. Special tests were carried out to check the uniformity of the blowing and the cross flow uniformity of the boundary layer.

The velocity profiles and turbulent transport characteristics were measured by hot wire anemometry using single wire (5 μm) and X-wire (2.5 μm) probes. All experiments were carried out at approximately the same reference Reynolds number $Re_\theta = 2550$ measured just upstream of the injection strip. The boundary layer thickness, δ, at this station was 41.3mm.

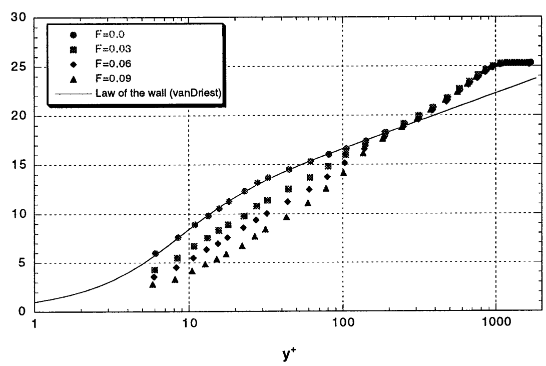

Figure 1: Mean velocity profiles at x=-0.06m, scaled with C_f for $F = 0$.

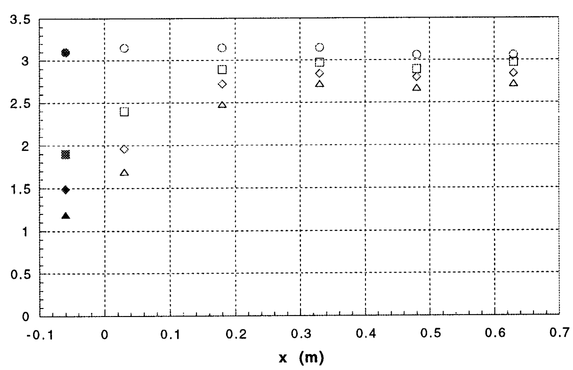

Figure 2: $10^3 \times C_f$ as function of x and F. ○ F=0, □ F=0.003, ◇ F=0.006, △ F=0.009. Filled symbols: Above blown strip.

RESULTS

The effect of surface blowing on the logarithmic layer has been studied by e.g. Simpson (1970) and Baker and Launder (1974). In the present experiment the streamwise extent of the injection region is too short (less than 3δ) for the inner flow to fully adapt to the new boundary condition at the wall. This is demonstrated in Fig. 1, where the measurements at x = -0.06 m were all scaled using C_f from the unblown case. (The origin for x was set at the trailing edge of the injection strip, which extends -0.12 $m \leq x \leq 0$ m). The profiles show that the flow outside $y^+ \approx 200$ is unaffected by the blowing.

In order to obtain reliable data of C_f also for the blown case, it was found essential to fit the data to a wall function which extends down to the viscous sublayer and assure a good data resolution near the wall. Therefore an extension of the van Driest (1956) law of the wall including the effect of surface injection was used (see. e.g. Schetz and Nerney, 1977)

$$U^+ = \int_0^{y^+} \frac{2\left(1 + U^+ V_w^+\right) dy^+}{1 + \sqrt{1 + \left(1 + U^+ V_w^+\right)\left(2\kappa y^+ f\right)^2}} \quad (1)$$

where f is the van Driest damping function, modified to include injection (see Cebeci, 1973). The skin friction coefficients obtained in this way are shown in Fig. 2 as filled symbols. For the stations downstream of the injection strip the skin friction coefficient was obtained using the same equation with $V_w^+ = 0$.

Downstream of the injection strip a new wall sublayer is quickly established. This leads to a triple layer structure, as demonstrated by the stresses shown in Fig. 3 to 6. In the near wall region ($y/\delta <$ 0.05) and the outer layer ($y/\delta > 0.6$), the stresses are unaffected by the blowing rate. The stresses in the intermediate layer are significantly increased and this effect was found to decay very slowly. It is apparent from the wall shear stress distribution (Fig. 2) that the decay distance is longer than the $x/\delta \approx 23$ range covered in this investigation. It is interesting however to note that at a given x position, the y/δ range over which the stresses are increased appear to be very little sensitive to the blowing rate. This complies with the findings of Bradshaw *et al.* (1967), who showed that the shear stress information propagates through the boundary layer along characteristics. If the mean flow is little affected by the changed boundary condition, which is the case except in the immediate vicinity of the injection strip, the direction of the characteristics and therefore the extent of the intermediate layer remain the same.

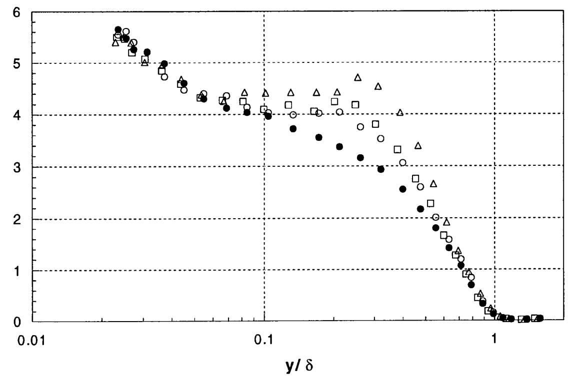

Figure 3: $\overline{u^2}^+$ at $x = 0.33m$, scaled with C_f for $F = 0$. ● F=0, ○ F=0.003, □ F=0.006, △ F=0.009

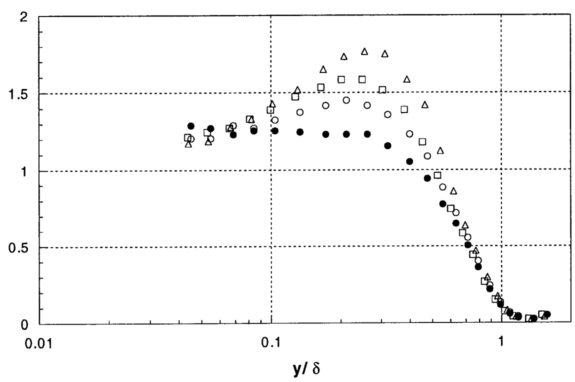

Figure 4: $\overline{v^2}^+$ at $x = 0.33m$, scaled with C_f for $F = 0$. Symbols as in Fig. 3.

Based on the single wire $\overline{u^2}$ measurements, the inner and outer limits of the affected layer for $F = 0.006$ are shown in Fig. 7.

Despite the considerable perturbations of the stresses with respect to the unblown condition, no spectral changes with respect to the blowing rate were found. Fig. 8 and 9 show the u and v power density spectra measured at $x = 0.18\ m$ and y/δ=0.2 for the unblown case and for the highest blowing rate. The location chosen is roughly in the midle of the intermediate layer and only about 4δ downstream of the strip trailing edge. The spectra have been normalized so that

$$\int_0^\infty \phi\,(ky)\,d\,(ky) = 1 \qquad (2)$$

where k is the streamwise wave number $k = 2\pi f/U$. The energy distribution for the two cases

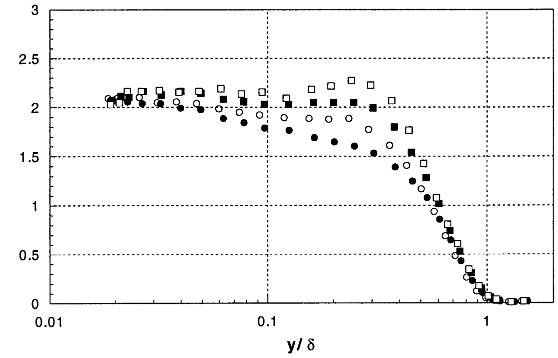

Figure 5: $\overline{w^2}^+$ at $x = 0.33m$, scaled with C_f for $F = 0$. Symbols as in Fig. 3.

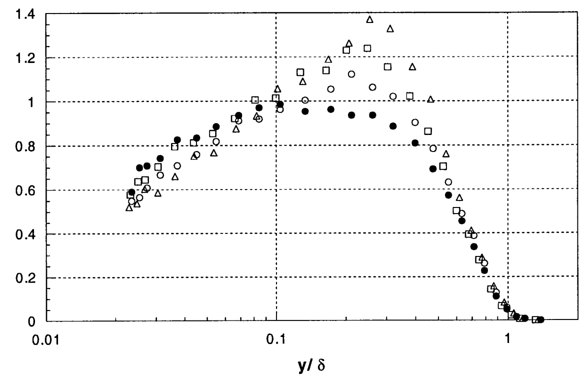

Figure 6: $-\overline{uv}^+$ at $x = 0.33m$, scaled with C_f for $F = 0$. Symbols as in Fig. 3.

shown are almost identical, with no apparent increase in energy level at any wave number. (The spectra for the other blowing rates were found to collapse with those shown and the same insensitivity to the blowing rate was found for all stations). This indicates that no additional length scales are introduced by the blowing and confirms that even though the stress levels are changed considerably, the time scale for the spectral transfer of energy is sufficiently short to obtain local equilibrium. Hence the local degree of anisotropy has not been changed by the blowing. This is further supported by the ratios between the stresses (Fig. 10 and 11). The ratio $\overline{v^2}/\overline{u^2}$ is frequently taken as a rough measure of flow anisotropy, as these are the two normal stresses which will be most different in a boundary layer. Except for the near wall region (y/δ <0.1), where the measured $\overline{v^2}^+$ appears to have been overestimated, the stress ratio $\overline{v^2}/\overline{u^2}$ and the shear coefficient $R_{uv} = -\overline{uv}/\sqrt{\overline{u^2}\ \overline{v^2}}$ are in

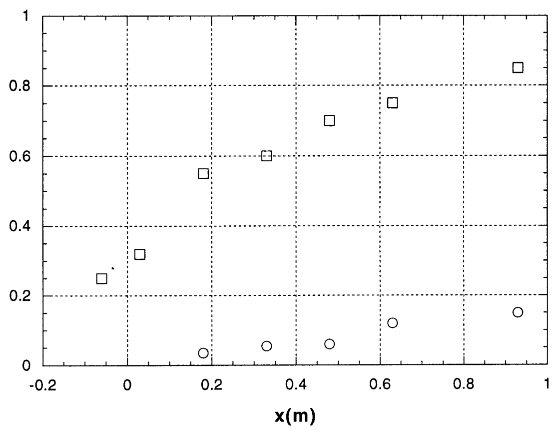

Figure 7: Inner- and outer limits of intermediate layer. ○ δ_i, □ δ_o

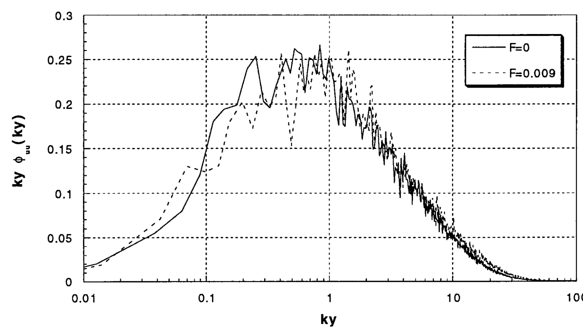

Figure 8: u spectrum at $x = 0.18m$ and y/δ=0.2.

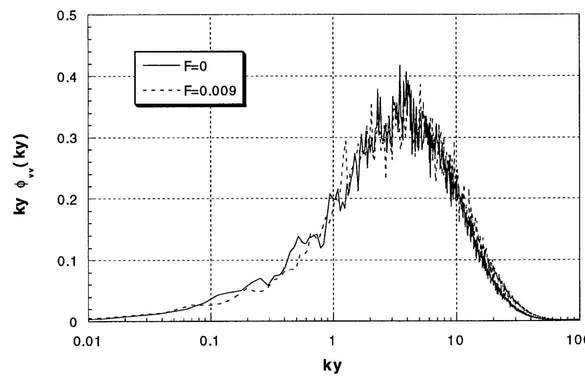

Figure 9: v spectrum at $x = 0.18m$ and y/δ=0.2.

good agreement with the DNS data of Spalart for an unblown boundary layer and show no sensitivity of the blowing rate.

The present measurements therefore do not give support to the findings of Senda *et al.* (1981), who claimed that surface injection tends to make the flow more isotropic. This conclusion was derived based on measurements of the streamwise and lateral Taylor micro scales. The injection strip in the present experiment is rather short, so it is possible that injection over a large area may lead to larger changes. Considering the insensitivity of the anisotropy in the large scale motion found in the present data, it appears however unreasonable to expect significant reductions in the anisotropy in the small scale motion even for a fully blown surface.

However, the present measurements did confirm their finding that the length scales of the small scale motions are reduced. Fig. 12 shows the Taylor micro scale, defined as

$$\lambda = \frac{\sqrt{\overline{u^2}}}{\sqrt{\overline{\left(\frac{\partial u}{\partial x}\right)^2}}} \tag{3}$$

which indicates a systematic reduction in λ in the intermediate region as the injection rate is increased. Similar reductions were also found in the Kolmogorov and mixing length scales.

Although there is no preferred spectral changes in the flow, this does not mean that the structural balance in the flow is unaffected. The increased shear stresses in the interaction region between the inner and outer layers, combined with larger velocity gradients, lead to significant increases in the turbulent production of kinetic energy as the blowing rate increases (shown for $x = 0.18\ m$ in Fig. 13). The turbulence production was found to be enhanced throughout the entire boundary layer in the blown cases. At $y/\delta \approx 0.2$ the production was found to increase by a factor of 2.5 at this station for the highest blowing rate. This agrees with the findings of Sumitani and Kasagi (1995) who observed that the turbulent production increases near a surface with injection and is reduced if suction is applied.

The effect of the blowing rate on the dissipation rate was found to be even higher. The dissipation was estimated from the inertial subrange assuming that

$$\epsilon = \frac{2\pi}{U}\left[\frac{\overline{u^2} f^{5/3}\phi_{uu}(f)}{C}\right]^{3/2} \tag{4}$$

where the Kolmogorov constant was taken to be $C = 0.53$. Close to the wall the dissipation rate is always less than the production. This is expected, since it leads to the outward diffusion of turbulent energy necessary for the boundary layer to grow downstream. However, as the blowing rate increases and the stresses in the intermediate range are enhanced, this leads to a significant increase in the dissipation rate in this region and it was found that the dissipation is increased even more than the rate of production (Fig. 13). This causes a significant imbalance between the production and dissipation rates in the intermediate layer.

As the boundary layer thickness and profile shape at this distance from the injection strip is very little affected by the surface blowing, there is little reason to expect any large changes in the turbulent advection terms. Hence it is primarily the diffusion terms which are affected. The pressure diffusion can not be measured with available techniques, but its contribution to the diffusion term is normally found to be negligible except very close to the wall (Spalart, 1988, Sumitani and Kasagi, 1995). In the turbulent diffusion term $\partial(\overline{vk})/\partial y$, the term $\overline{vw^2}$ can not be measured with conventional x-wires techniques, so the complete effect of the surface injection on the turbulent diffusion may not be assessed. However, $\overline{u^2v}$ and $\overline{v^3}$ were both measured and were found to respond similarly to the injection.

The variation of $\overline{u^2v}^+$ has been shown in Fig. 14. It is seen that the surface blowing affects the intermediate layer by reducing $\overline{u^2v}^+$ for $y/\delta < 0.2$ and causing an increase for $y/\delta > 0.2$. The very large gradient causes a strong outward diffusion from $y/\delta \approx 0.1$. A similar trend was also found for $\overline{v^3}^+$ and is therefore also expected in $\overline{vw^2}^+$. These trends corroborate the findings from the production and dissipation terms, since the estimated diffusion will compensate for the imbalance between production and dissipation in the outer layer caused by the surface blowing.

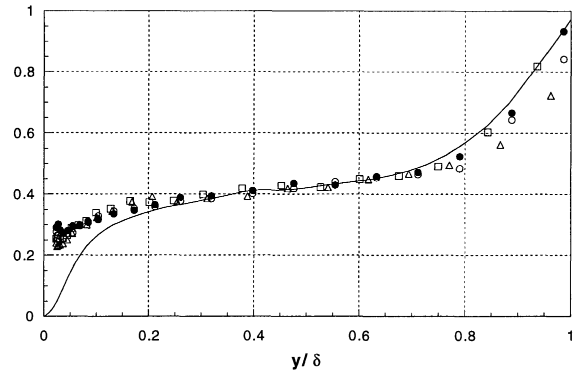

Figure 10: Stress ratio $\overline{v}^2/\overline{u}^2$ at $x = 0.18m$. Symbols as in Fig. 3. Line: Spalart (1988), Re_θ=1410

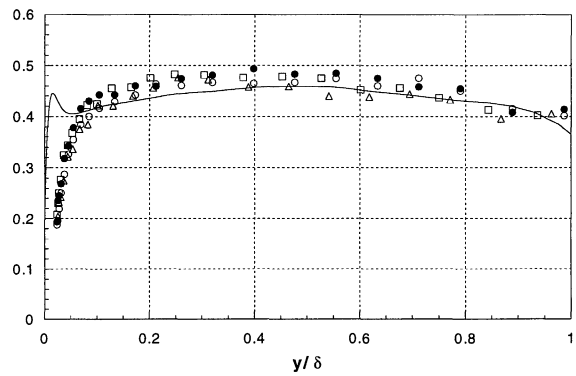

Figure 11: Correlation coefficient R_{-uv} at $x = 0.18m$. Symbols as in Fig. 3. Line: Spalart (1988), Re_θ=1410

CONCLUSION

The boundary layer response to injection through a short porous strip was investigated experimentally in a wind tunnel. The injection caused a sudden reduction in surface friction which prevailed for a very long streamwise distance. In the present experiment, a reduction in C_f was clearly detectable over the entire range investigated (about 23 times the boundary layer thickness at the start of the injection) for all blowing rates.

Downstream of the injection region a conventional inner layer was quickly re-established and even at the first measurement station ($x = 0.03$ m, corresponding to $x/\delta \approx 0.6$) the beginning of a new logarithmic region was detectable. However, the modified logarithmic region developed by the surface injection persisted for a considerable distance. This made it difficult to evaluate C_f from the logarithmic region alone. Therefore the van Driest (1956) formulation was applied, so that data in the buffer and viscous sublayer could be used as well.

No effect of the blowing was found in the outer layer. However, in the intermediate layer considerable increases in all the Reynolds stresses were observed. This is primarily caused by an increase in the shear stresses above the blown strip, which significantly increases the turbulent production. This in turn causes an increase in $\overline{u^2}$ which is redistributed to the other normal stresses. By inspecting the ratios of the stresses it was found that the time scale of redistribution is much shorter than the de-

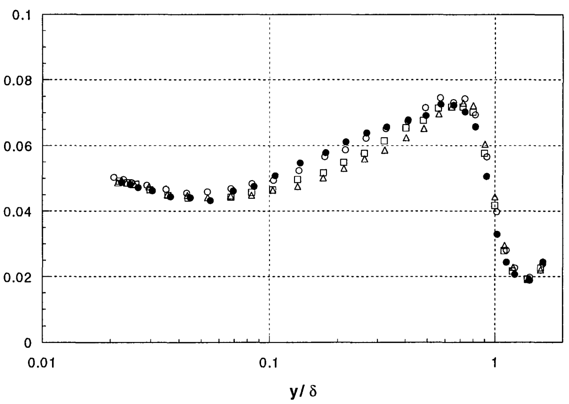

Figure 12: λ/δ at $x = 0.18m$. Symbols as in Fig. 3.

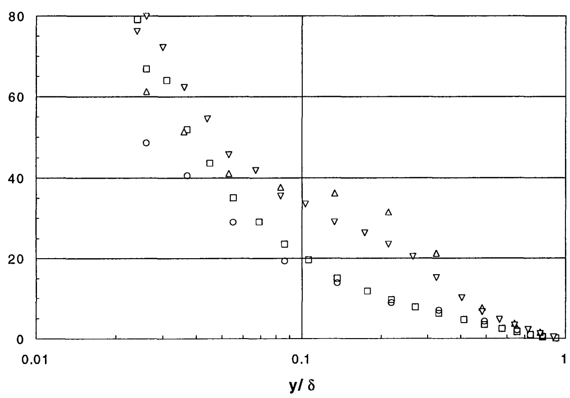

Figure 13: Production and dissipation measured at $x = 0.18m$, scaled with C_f for $F = 0$. $-\overline{uv}\frac{\partial U}{\partial y}\left(\delta/u_\tau^3\right)$: ○ F=0, □ F=0.009. $\epsilon\left(\delta/u_\tau^3\right)$: △ F=0, ▽ F=0.009.

cay time of the perturbation caused by the surface blowing. Therefore the ratios between the stresses, as well as the spectral distributions of energy, remain the same. It was thus concluded that the structural changes to the flow must be small even though the turbulent production, diffusion and dissipation rates of turbulent kinetic energy were all severely modified.

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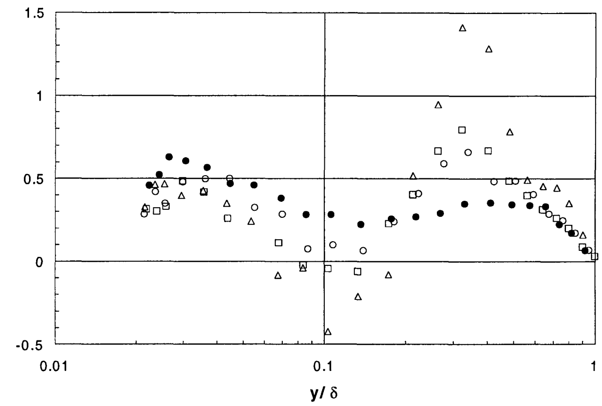

Figure 14: Triple correlation coefficient $\overline{u^2v}^+$ at $x = 0.18m$, scaled with C_f for $F = 0$. Symbols as in Fig. 3.

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