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THE REATTACHED TURBULENT SHEAR LAYER BEHIND A TWO-DIMENSIONAL CURVED HILL

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ABSTRACT

Measurements were conducted in a reattached shear layer over a splitter plate behind a two-dimensional curved hill. The ratio of the boundary layer thickness at separation to the height of the hill is approximately 0.3. The results show that the mean flow downstream of reattachment in the inner region adjusts itself by re-establishing the law of the wall quickly while the outer layer profile exhibits a 'dip-below-log-law'. The profiles of Reynolds shear stress show the recovery of the turbulent flow is rather slow, lagging the recovery in the streamwise pressure gradient. The behaviour of the normal stresses indicate that the wall tends to inhibit the normal component of velocity fluctuations as the flow reattaches and relaxes. The distributions of stresses in the outer layer has characteristics reminiscent of the mixing layer that shrouds the separation bubble.

NOTATION

C_f	local skin friction coefficient
C_{pw}	static pressure coefficient at the wall
U_{ref}	reference velocity
U_τ	friction velocity
U^+	U/U_τ
y^+	yU_τ/ν
$-\overline{uv}_{max}$	maximum shear stress.
U, V, W	mean velocity along x, y and z axes
$\overline{u^2},\overline{v^2},\overline{w^2}$	Reynolds normal stresses.
$-\overline{uv},-\overline{uw}$	Reynolds shear stresses.
x	axis along streamwise direction
y	axis normal to the wall
z	axis along spanwise direction
ν	kinematic viscosity
δ_{99}	boundary layer thickness.

INTRODUCTION

Many fluid flows of engineering interest are 'complex' in that they are either governed by extra rates of strain additional to simple shear or by the interaction between shear layers. Prediction of complex flows has been the aim of many researchers and reliable modelling requires not only validation through test cases but also a better understanding of the inherent phenomena underlying a complex turbulent flow. The present study is an attempt to improve our understanding of one such complex flow, specifically the relaxation of a shear layer after incipient separation and reattachment. Experiments have been conducted in a shear layer which reattaches and relaxes on a splitter plate behind a two-dimensional curved hill after separating on the leeside of the hill as shown in figure 1. The shear layer prior to separation suffers from the influence of streamwise pressure gradients and streamline curvature alternating in sign. A detailed account of the changes in the flow behaviour, including that in the turbulence prior to separation point, is given in Baskaran, Smits & Joubert (1987). The present paper discusses results pertaining to the relaxing shear layer after reattachment.

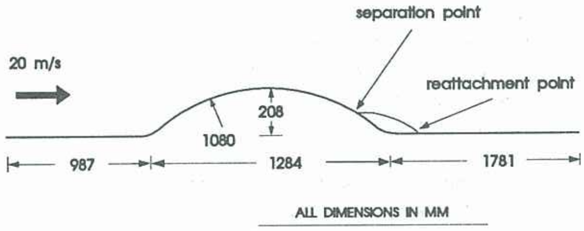

Figure 1. Two-dimensional curved hill.

Several investigators have studied the reattaching shear layer in the form of flow behind an obstacle or flow over a step in the surface. The simplest of the reattaching shear layer geometry that has been treated extensively in the literature is that behind a backward facing step where there is a well defined separation point located in the corner of the step (for a review, see Simpson, 1985), even though the reattachment point is ill defined. In contrast, the flow in the present study separates incipiently, that is the skin friction falls to zero due to adverse streamwise pressure gradient at the separation point, whose location is stationary only in the mean sense. The ratio of the shear layer thickness at separation to the height of the hill is about 0.3, and the perturbation is 'overwhelming' in the sense of Bradshaw & Wong (1972).

Earlier investigations of curved wall turbulent flows in which incipient separation and subsequent reattachment occur include those studied by Gerston, Herwig & Wauschkuhn (1980) and Wei & Sato (1984). No turbulence measurements were conducted in the earlier, and the experiments were intended to check the existence of separation bubbles for different values of the ratio of boundary layer thickness to height of the curved step. In the later, measurements reported were confined to the region between separation and reattachment with little emphasis on the relaxation of the flow downstream of reattachment.

In the present study measurements were focused on the post-reattachment behaviour of the flow, especially early stages of the relaxation process; the last measurement station is only 6 times the height of the hill from the reattachment point. The results, while showing the expected trend towards recovery to two-dimensional undisturbed values, indicate the shear layer is still far from complete recovery at the last measurement station. In particular, the primary shear stress appears to be recovering slowly even though the pressure gradient has relaxed significantly. Spanwise profiles of skin friction coefficient show there is inhomogenity in the flow to a certain degree. The overall flow behaviour seems to correspond to the behaviour of a free shear layer affected by the presence of the wall.

APPARATUS AND TECHNIQUES

The work was performed in the Melbourne University large closed-return wind tunnel facility. The working section is octagonal, measuring 1.68 m by 1.3 m with a length of 6.54 m. The walls of the test section were slotted with an open-to-closed ratio of 4.9% to reduce solid blockage. The adjustable side walls were set to give a negligible longitudinal pressure gradient along the centreline of the empty tunnel. The model was positioned vertically and the slots in the roof and the floor were sealed to prevent end leakage. A 2 mm diameter trip wire located at 153 mm from the leading edge of the front flat plate was used to promote transition. Measurements were taken at a nominal tunnel free stream velocity, U_{ref}, equal to 20 ms^{-1} giving a Reynolds number of 1.33×10^6 per meter.

Skin friction coefficients were obtained using 1.08 mm and 1.26 mm diameter Preston tubes with the calibration of Patel (1965), and Clauser charts using constants of 0.41 and 5.2. Mean velocity profiles were obtained using a 0.5 mm diameter round pitot tube and corrected for displacement effects. Turbulence measurements were made using both normal and crossed hot-wires. Wollaston wires with a filament diameter of 5μm were cold soldered to prongs of the probe and etched to give an active length of 1.2-1.5 mm. The construction of the crossed-wire probe was such that it could be rotated accurately about its axis through 90 degrees, enabling measurements in two perpendicular planes (referred to as 'UV mode' and 'UW mode') to be made at a point. Unlinearised constant temperature hot-wire anemometers were used. The wires were dynamically calibrated using the procedure given by Perry (1982). The probe was pitch aligned close to the wall before measurement such that the probe's pitch angle was the same as that during calibration. All calibrations and measurements were made on-line using a PDP11/10 digital computer equipped with analog-to-digital converter. For each wire, four sets of 8000 samples were collected at a frequency of 200 Hz at a given point in the flow during measurement.

As the turbulence levels are high in the present type of flow some comments are needed regarding the limitations and accuracy of measurements despite our best intentions to obtain reliable data using techniques such as the dynamic calibration procedure for hot-wires. The longitudinal turbulence intensity reaches a maximum value at about one quarter of the boundary layer thickness especially during the initial stages of development of the flow and the corresponding turbulence level (ratio of root mean square value to local mean velocity) is 20 percent. As a consequence, the mean velocity inferred from the pitot tube traverses is underestimated by about 8 percent near the maximum intensity location. However, at distances close to the wall the agreement with the independent normal hot-wire measurements is good enough to infer the friction velocity reliably. The shear stress profiles also extrapolate to the wall satisfactorily. The mean velocities measured by the pitot probes presented here are not corrected for the effects of turbulence. Similarly, the hot-wires are well known to suffer at high turbulence levels due to exceeding the cone of instantaneous velocities it is capable of measuring (Lim, 1985). The scatter in the longitudinal component of mean square velocity measured in the two modes near the region of maximum intensity or shear stress is attributed to this as the same was accurately measured (within 3 percent) by the same technique at all locations ahead of separation point (Baskaran et al., 1987). The scatter band for the longitudinal mean velocity component is about ± 3 percent and for the corresponding intensity component is ± 8 percent about a mean near the maximum stress location in the hot-wire measurements.

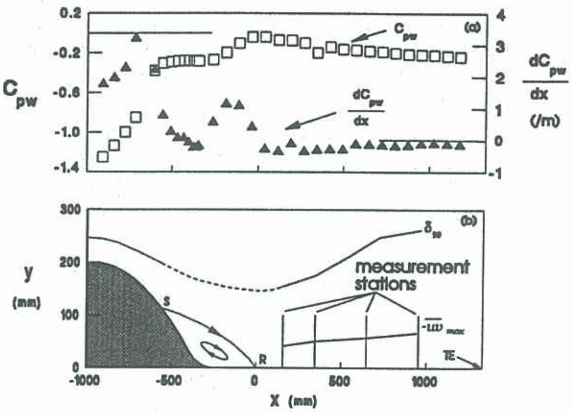

Figure 2. (a) Surface static pressure and pressure gradient distributions; (b). Profile of hill, loci of δ_{99} and $-\overline{uv}_{max}$ and measurement stations

RESULTS AND DISCUSSION

Figure 2(a) shows the surface static pressure distribution and its streamwise gradient from the summit of the hill to the tailing edge of the rear splitter plate. The locations of the separation and reattachment points, measurement station, loci of the boundary layer thickness, δ_{99} , and the maximum shear stress, $-\overline{uv}_{max}$, are shown in figure 2(b). Note that all locations, including the stations where traverses were made are referred to the 'reattachment point' as the origin. The locations of the 'separation' point and the 'reattachment point were inferred by extrapolating the skin friction coefficient to zero. The location of the reattachment point corresponds to the maximum in C_{pw}. The streamwise pressure gradient is favourable downstream of reattachment. The streamwise distributions of local skin friction coefficient, C_f , are compared in figure 3. The values obtained using the log-law fit to pitot tube data are in good agreement with those obtained using Preston tubes, whose calibration in turn relies on the existence of log-law. Fitting the log-law to the mean velocities measured by a normal hot-wire gives C_f values which are not significantly different from those inferred from that using pitot tube data. The downstream development of the spanwise distribution of C_f , shown in figure 4, indicates a strong inhomogenity across the flow especially close to the reattachment point. The distribution across the

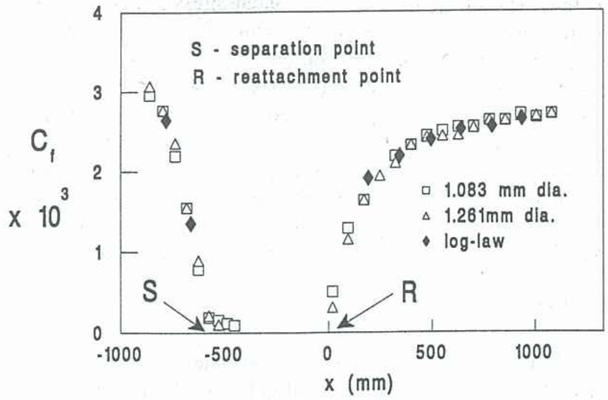

Figure 3. Streamwise distribution of skin friction coefficient.

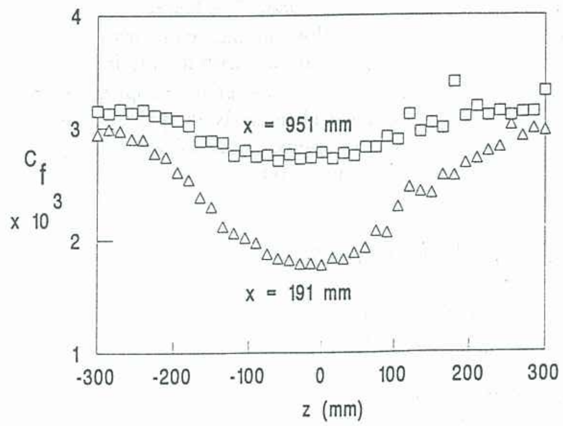

Figure 4. Spanwise distributions of skin friction coefficient.

last station, particularly the attenuation of the minimum in C_f even though shows a trend towards two-dimensionality, indicates that the flow still suffers from spanwise inhomogenity, but to a lesser degree. Similar behaviour of C_f distribution in the spanwise direction was observed by Smits (1982) in a reattached shear layer flow behind a bluff plate in the same wind tunnel. The centreline of the model corresponds to z =0 in figure 4.

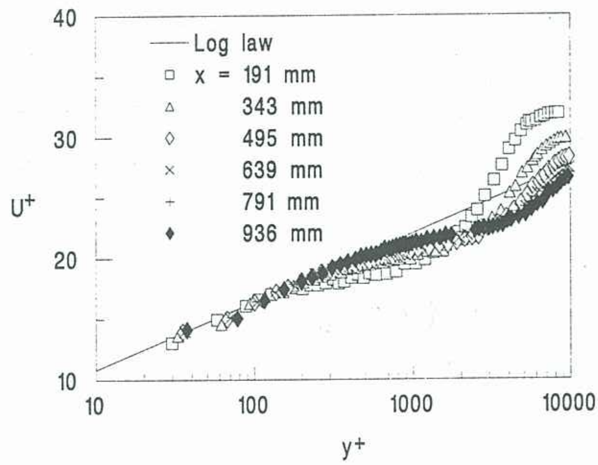

Figure 5. Mean velocity profiles in wall co-ordinates.

The mean velocity profiles obtained from pitot tube traverses are plotted in wall coordinates in figure 5. The law of the wall after reattachment of the flow appears at a fetch as small as one hill height. A quick re-emergence of log-law is usually found in many perturbed turbulent boundary layers undergoing relaxation towards undisturbed state. All profiles exhibit 'dip-below-log-law' which was observed in flows behind backward facing steps and in turbulent boundary layers over concave walls. In the preset case, the dips are exaggerated due to the effect of turbulence on the pitot tube readings. These dips are normally interpreted as indicative of an increase in turbulence length scale such as the dissipation length.

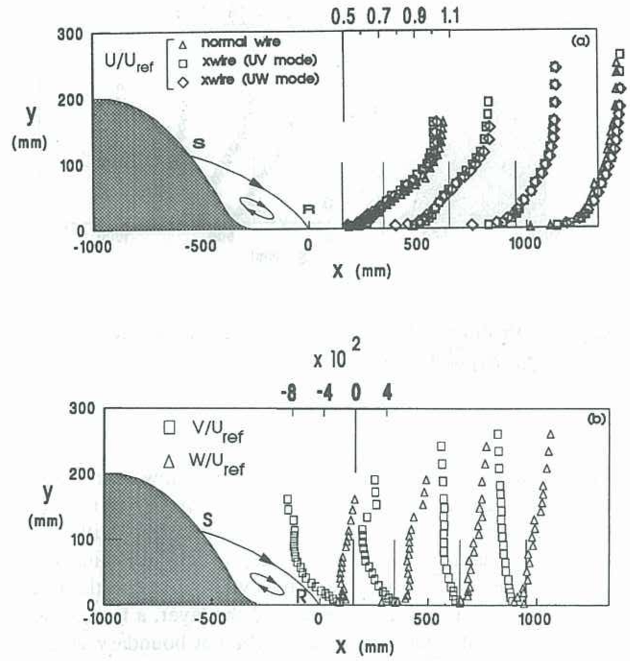

Figure 6. Profiles of mean velocity components.
(a) U/U_{ref}; (b) V/U_{ref} and W/U_{ref}.

Figures 6(a) and 6(b) show profiles of the mean velocity components, U, V and W, obtained using hot-wires. In order to identify absolute changes, these components including the turbulent stresses were nondimensionalised with respect to the reference velocity, U_{ref}. The profiles of U exhibit inflexions at the first two stations. The negative values of V whose magnitude increases as the local free stream is approached are consistent with the expected trend due to the mixing layer flow inclined to the surface. The streamlines close to the surface are necessarily parallel and the normal velocity component is close to zero. The gradual decrease in its magnitude with the downstream distance indicates a longitudinal concavity of mean streamlines of the flow. The lateral component of mean velocity, W, which is measured with respect to the centreline, remains more or less the same in the outer half of the flow at the last three stations. The existence of finite, but small values for V and W at the last station could be interpreted as the departure of the mean flow from two-dimensionality.

The streamwise development of the profiles of the Reynolds normal stress components is shown in figure 7. The profiles of $\overline{u^2}$ in figure 7(a) at the first two stations exhibit a pronounced maxima and almost constant distributions across the layer up to the point of $-\overline{uv}_{max}$ at the last two stations. The behaviour of the other two components (figure

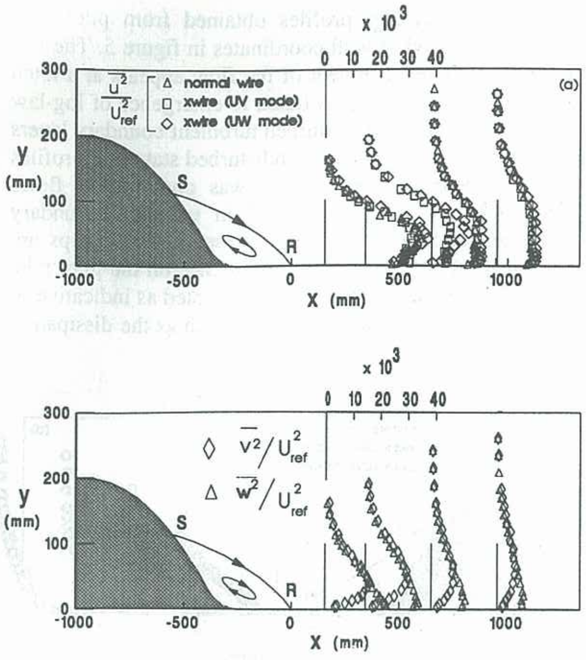

Figure 7. Profiles of Reynolds normal stress components. (a) $\overline{u^2}/U^2_{ref}$; (b) $\overline{v^2}/U^2_{ref}$ and $\overline{w^2}/U^2_{ref}$.

7b) exhibit two distinct regions across the flow, one where $\overline{v^2} < \overline{w^2}$ and the other where $\overline{v^2}=\overline{w^2}$. The dividing line between the two regions closely correlates with the maximum primary shear stress location. An interesting fact about profiles of $\overline{v^2}$ is that it assumes values close to the wall as small as it is in outer 20 percent of the layer, a feature not characteristic of typical flat plate turbulent boundary layers. The tendency for $\overline{v^2}$ to fall to zero as the wall is approached shows the inhibitive or the damping effect of the wall on normal component of velocity fluctuations in the mixing layer flow. This wall constraint effect suggests that pressure fluctuations at the wall may be significant The region where the two components are equal is characteristic of the mixing layer flow rather than a boundary layer flow where $\overline{w^2} > \overline{v^2}$ everywhere, except close to the edge.

The profiles of Reynolds shear stress components, $-\overline{uv}$ and $-\overline{uw}$ are shown in figure 8, including the values at the surface inferred from figure 3. To be consistent with the nondimensionalisation of the quantities, the wall values are referred to the reference velocity . The primary shear stress profiles extrapolate fairly well to the independent wall values. The inconsistency of the shear stress gradient normal to the surface with the sign of streamwise pressure gradient suggests a lag in the relaxation of the stress field. The existence and attenuation of the maxima in the primary shear stress along the flow are characteristics in common with free shear layer affected by the wall. The study by Wood & Bradshaw (1984) in a mixing layer affected by wall applied to the present work suggests that the redistribution process is likely to be very active and responsible for the recovery of the flow to that corresponding to the undisturbed state.

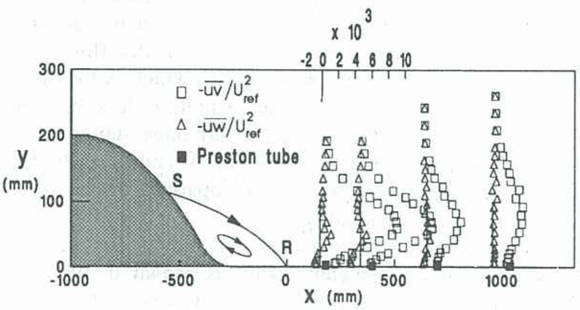

Figure 8. Profiles of Reynolds shear stress components.

CONCLUSIONS

Experiments in a reattached turbulent flow behind a two-dimensional curved hill lead to fairly a broad conclusion that the recovery of the flow towards the two-dimensional undisturbed state is slow. The redevelopment of the shear stress in the reattached flow appears to lag the recovery of the streamwise pressure gradient. The behaviour of turbulent stresses shows that the flow in the reattached shear layer possesses characteristics common with the mixing layer flow with the wall acting as a constraint in damping the turbulence. The mean flow has characteristics typical of perturbed shear layers such as the re-emergence of and the dip-below-log-law despite the spanwise inhomogenity that exists in the flow.

ACKNOWLEDGEMENTS

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