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EXPERIMENTAL STUDY OF TURBULENT FLOW ALONG A STREAMWISE EDGE (CHINE)

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Abstract

An experimental study of the development of the turbulent boundary layers along a streamwise chine will be presented. This flow represents a special class of three-dimensional turbulent boundary layers, where secondary flow is induced by inequality of Reynolds stresses around the edge. The direct effect of this edge flow is to increase the drag force. A recent study along a right-angled streamwise edge was given by Panchapakesan & Joubert (1998 and 1999). These measurements provided, in qualitative terms, the general behaviour expected from this class of flow as revealed by Elder (1960), but they suffered from asymmetry about the edge bisector due to overall flow geometry, especially side wall contamination. The developing edge vortices were affected unevenly by the growing corner vortices. By altering the effect of the tunnel side walls, quasi-symmetry was achieved. Our measurements indicate symmetry about the bisector with a maximum deviation of 5 percent. Measurements were carried out on a 6 meters long test model at a station 4.665 m from the trip wire. This downstream station was chosen with an understanding that symmetry at this station would likely ensure symmetry everywhere upstream.

Introduction

The study of the turbulent boundary layer developing over a chine has great significance in various engineering applications. The three dimensional effect of this flow includes many of the mechanisms seen in turbulent flows encountered in practice such as flow over intersecting surfaces found in ship's hulls, trains and trucks.

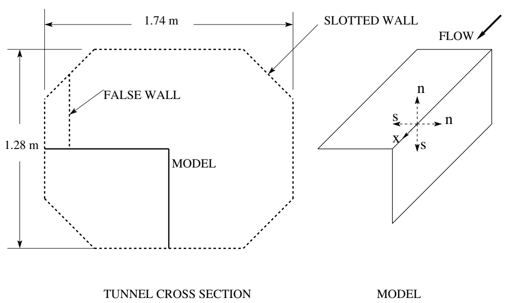

Figure 1: Schematic diagram of tunnel cross section and model.

Ideally, a chine is formed at the intersection of two surfaces. Flow past the lateral edge of a finite flat plate aligned with the streamwise direction have been studied by Elder (1960) and Davies & Young (1963). With the addition of a second flat plate held normal to the first, but parallel to the freestream, a streamwise corner region is formed (see Figure 1). Since the work of Carrier (1946) a number of experimental studies of the boundary layer in the internal corner region have been reported. But it is only in the University of Melbourne that a series of experimental investigations on the outside corner has been studied by Panchapakesan & Joubert (1998 and 1999). In spite of its simple geometry, the flow development exhibits substantial complexity with three dimensionality driven by secondary flow.

The measurements of Panchapakesan & Joubert (1998 and 1999) showed, in qualitative terms, consistency of the general behaviour reported by Elder (1960). Their measurements suffered from asymmetry about the edge bisector which is non-negligible and persistent. It was assumed that this asymmetry was caused by side wall contamination. The horizontal flat plate width of their model was 0.87 m whereas the vertical plate width was 0.64 m. This affected the developing edge vortices unevenly, due to the growing corner vortices. With the introduction of some changes to the test model geometry, a quasi-symmetric flow is achieved at the last measuring station.

Literature survey

In last the six decades the flow along the streamwise internal corner has attracted a lot of attention from researchers. This flow geometry is pertinent to complex flow conditions that occur near wing body junctions, wing-fin assemblies, the roots and tips of blades in turbomachinary, etc. Flow development along an internal corner has been studied in detail both as part of a duct flow and as an unconfined corner flow. Such flow in a duct was carried out by Brundrett & Baines (1964) Gessener & Jones (1965), Perkins (1970) and many others. A number of researchers of the University of London carried out studies on unconfined internal corner flow as reported by Zamir & Young (1970) and Majola & Young (1972). All these studies revealed that if the duct flow is fully developed then the streamwise gradients of turbulence quantities along the axial direction should be zero, whereas these gradients are not zero in the unconfined corner flow.

The geometries investigated by Elder (1960), which were the lateral edge of a finite flat plate and small aspect ratio bars aligned with the flow, are the ones that were the basis of the series of experiment carried out in the University of Melbourne. Elder in his investigation used Pitot tubes and surface tubes to measure the velocity field and wall shear stresses respectively. He also used a vortameter to deduce the nature of the secondary flow.

The study of Panchapakesan & Joubert (1998) presented mean flow measurements. The variation of the boundary layer thickness in the transverse directions for three measurement stations clearly shows asymmetry of flow about the bisector (Figure 2). The initial thinning of the boundary layer as we move towards the corner and a subsequent thickening due to the secondary flow was also observed by Elder. This suggests that the secondary flow is driven away from the corner along the bisector and returns back towards the wall farther from the corner.

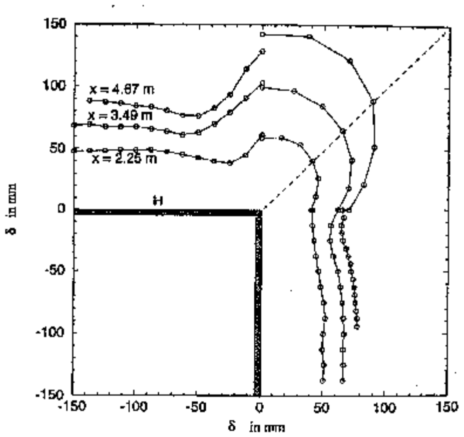

Figure 2: Lateral boundary layer thickness variation (looking upstream), after Panchapakesan & Joubert (1998).

The investigation of Panchapakesan & Joubert (1999) included pressure coefficients (Cp) and skin friction coefficients (C_f) distributions and streamwise turbulence intensity profiles. The measured value of C_f changed sharply over the corner and the influence of the secondary flow was observed to be different on the two surfaces. The extent of the region of influence of the corner is of the order of a two-dimensional boundary layer thickness. From their Cp distribution they concluded that the asymmetric development was unlikely to be caused by an external presure gradient. Over the horizontal surface the turbulence close to the wall and near the corner is attenuated but is enhanced in the outer region in comparison with the turbulence profiles far from the corner. The profiles over the vertical surface show the effect of the asymmetric mean flow field on the turbulence. The turbulence is attenuated through the boundary layer as we move towards the corner.

Experimental apparatus and techniques

The new experimental set up is shown schematically in Figure 1. The chine model, with some essential changes, is the same as that used and described by Panchapakesan & Joubert. The test section of the tunnel has an octagonal cross-section with major dimensions of 1.28 m by 1.74 m as shown in Figure 1. The test section is constructed from aluminium slats with narrow gaps between them. The blockage effect of the models used in the test section is minimized by this construction. Air was supplied to the test section by a large closed circuit wind tunnel.

In the previous investigation two plane surfaces, constructed from varnished medium density fibre boards of half test section widths and running the entire length of the test section, made up the chine. In the present model 80 cm long flaps set at 10^0 to the main flow direction were attached at the end of the model to minimize interaction between flow over and beneath the test model surface. The model surface has been polished meticulously to a mirror like surface. Aluminium airfoils of a symmetric section were attached to the leading edges to avoid separation. A false side wall was prepared from wooden slats with narrow gaps between them to match with the overall configuration. The position of the false wall was adjusted until the flow symmetry was achieved.

The boundary layers were tripped with stainless steel wires of 1.2 mm size fixed to the boards at about 80 mm from where the aluminium airfoil and the chine boards meet. The trip wire was taken as the reference for axial distance measurements and the corner is the reference for transverse distances. As shown in Figure 1, x is the distance in the streamwise direction, whereas spanwise and normal directions are denoted by y or s and z or n respectively. The flow was investigated at 6.8×10^5 unit Reynolds Number corresponding to a nominal freestream velocity of 10.5 m/s. A Pitot tube of 0.7 mm diameter was used and was calibrated against the NPL Prandtl tube. Similarly a separate static pressure probe was also calibrated against an NPL static tube for measuring Cp distribution.

Preliminiary investigations

The primary effort was to produce symmetry in the flow geometry. Measurements of the mean velocity at the axial location of x=4.665 m, at 5 mm away from the edge on both surfaces agree well with the earlier measurements of Panchapakesan & Joubert (1998). This was carried out with the same model geometry without any false wall.

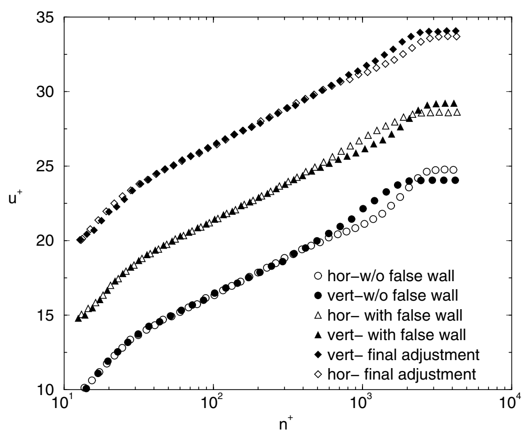

Figure 3: Adjustment for symmetry.

A false wall was then placed on the horizontal surface at 64 cm away from the edge with the intention of making both the surfaces of equal width. As shown in Figure 3, fully opposite trends of velocity profile were obtained. This phenonmenon confirmed the need of a false wall to bring about flow symmetry at the further downstream station. Accordingly the false wall was placed successively at 71.5 cm, 70.5 cm and 69.5 cm away from the edge and for each position velocity profiles at 5 mm away from the edge on both surfaces were measured. This process was continued until the symmetry was achieved to within 5 percent deviation margin. The final position of the false wall is at 69.5 cm away from the edge. The comparison is shown in Figure 3 and Table 1. Here δ_C is defined as Rotta-Clauser boundary layer thickness.

Comparison			
Parameter	Vertical	Horizontal	Percentage
δ_C	102.83mm	106.44mm	3.5
Re_θ	5169	5554	7.5
H	1.26	1.23	2.27
$Cf_{Clauser}$	3.4537e-03	3.5564e-03	2.97
$Cf_{Preston}$	3.5635e-03	3.4166e-03	1.58
Π	.173	.172	.6

Table 1: Comparison between parameters of mean velocity profiles on both surfaces at s=5 mm.

Results

Mean velocity

The mean flow velocity profiles are measured at x= 4.665 m. Profiles are obtained on both surfaces at 5, 15, 30, 50, 75, 100, 125 and 150 mm away from the edge. These profiles are plotted in Figure 4. The Macmillan correction is applied to the readings.

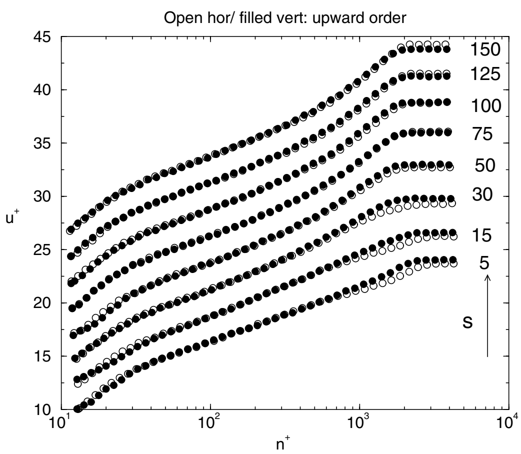

Figure 4: Velocity profiles at different spanwise stations, are shifted 5 unit upwards from previous ones, except for the first profile at s=5mm.

It is revealed that as we move further from the edge the asymmetry smears out gradually. The profiles completely collapse at a distance larger than 75 mm from the corner. This indicates that the boundary layer away from the edge develops as a standard two dimensional flat plate boundary layer as reported by Panchapakesan & Joubert (1998 and 1999). Beyond s=100 mm, there is again some asymmetry in the velocity profiles. This may be due to the influence of the growing corner vortices between the tunnel bottom wall and vertical surface and between the horizontal surface and false side wall.

Cp distribution

The streamwise pressure coefficient distribution, measured at a height of 240mm and 340 mm away from the edge, is presented in Figure 5. The introduction of flaps at the model end has extended the area of zero pressure gradient (ZPG) and there is only a minimum reduction in overall Cp distribution. The flap and narrow slats have prevented the development of a favourable pressure gradient in the test section. Thus the Cp was found to be well within +0.005 and -0.001. The effect of any longitudinal pressure gradient on flow development should be very small.

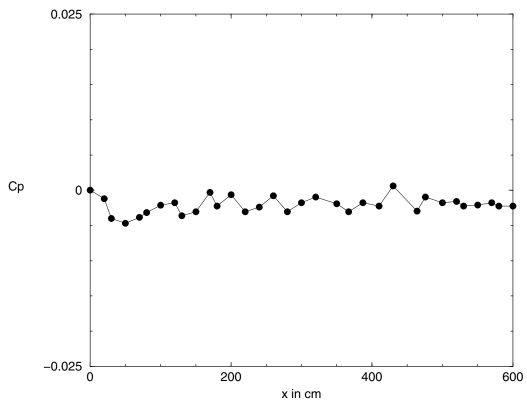

Figure 5: Streamwise Cp distribution.

Comparison of 2-D boundary layer velocity profile

Based on the assumption that at s= 100 mm we have a ZPG standard two-dimensional boundary layer, the velocity profiles on both surfaces are compared with that of Österlund (1999) at Re_θ 5500 as shown in Figure 6. The profiles collapse fairly well. Higher u^+ values are observed for our Pitot tube measurements compared to the Österlund (1999) hot wire results. This trend is similar to pipe flow measurements of Monty et al. (2001), which is also shown in Figure 6.

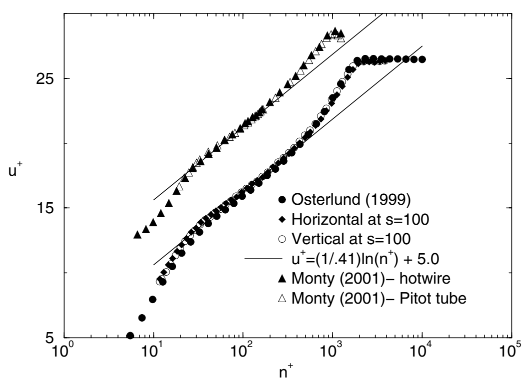

Figure 6: Comparision of 2-D velocity profiles at s=100 mm.

Isovelocity contour

The isovelocity contour plot is presented in Figure 7. To commensurate with the velocity profiles on both surfaces,

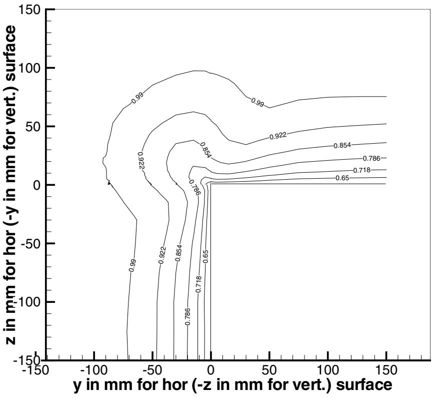

Figure 7: Isovelocity contour at x = 4.665 m (presented looking downstream).

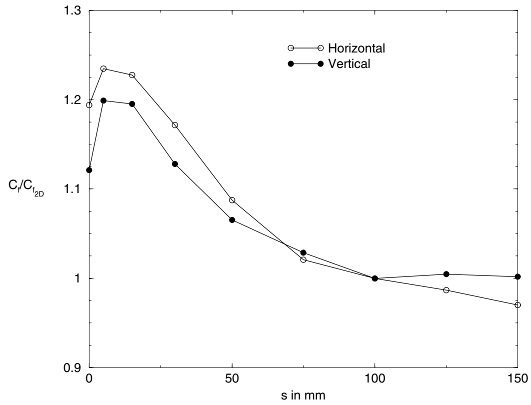

Figure 8: Spanwise C_f distribution at x=4.665m.

measurements of mean flow velocity were also taken in the corner regions at 5, 15, 30, 50, 70, 90, 110 mm from the corner. The edge of the boundary layer, (where u $=.99U_{ref}$) grows almost equally about the plane of symmetry. A small variation is observed near the edge (up to s=30 mm) which is also evident in Figure 4. This indicates that the outer region is strongly influenced by edge turbulence. The initial thinning and then thickening of the boundary layer as we move from the two dimensional region towards the edge, similar to that reported by Elder (1960) and Panchapakesan & Joubert (1998 and 1999), is also observed here. This is an indication of the presence of secondary flow. Further confirmation will be obtained from flow visualisation and x-wire measurements in future work. Zamir et al (1970), have shown from flow visualisation that the secondary flow is directed away from the edge bisector (plane of symmetry) in the case of an internal corner, whereas for the external corner, flow is directed towards the edge bisector and then flows back towards the wall.

Skin friction distribution

The variation of the skin friction coefficient based on Clauser's chart is presented in Figure 8. The variation is similar to that of Elder on his 22 cm wide flat plates, at a station x/width = 1.5. We found almost identical variation for the flow over the horizontal and vertical surfaces which is in contrast with Panchapakesan & Joubert (1998 and 1999)'s findings.

Conclusions

The mean flow measurements along the corner region of a chine is presented for the symmetrical flow over two orthogonal surfaces. The influence of the corner is observed up to one to two boundary layer thicknesses at the measuring station. Within this region of influence, right near the edge, the skin friction drops rapidly.

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