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TURBULENT SHEARED FLOW AROUND SURFACE MOUNTED PRISMS

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SYNOPSIS: This paper presents descriptions of the flowfield around rectangular prisms standing in turbulent boundary layers. The work is mainly concerned with the flow recovery downstream of prisms with differing geometries. Downstream recoveries are analysed in terms of non-dimensional groupings of the flow parameters. The non-dimensional groupings used are those that can be related, through physical arguments, to an effect on a major feature in the flow such as separations or mixing vortices. Flow around single prisms and arrays of prisms are considered and both two and three dimensional prisms are considered. Although much previous work is re-analysed some new data is presented; the only data excluded is that for prisms larger than the boundary layer thickness.

1 INTRODUCTION

The problem of flow around prisms submerged in a turbulent boundary layer has been extensively studied by previous workers. Most previous work is concerned with the relationship of prism drag to a range of non-dimensional groupings of flow parameters but some recent work (Hunt et al. (1977), Castro (1979)) has been concerned with flow in the vicinity of the prism. The present work is mainly concerned with boundary layer recovery downstream of a prism or an array of prisms and seeks to relate differences in the downstream flow to changes in a single non-dimensional group of flow parameters through physical arguments concerning large features of the flow (e.g. separated regions, mixing vortices). As most existing data is limited to centreline mean flow measurements, so is most of this work. Only data for prisms larger than the approaching boundary layer are excluded.

2 NOTATION

$c_f'/c_f'_u$ - skin friction coefficient relative to an upstream value
h - height of prism
G - Clauser's boundary layer shape parameter
k - surface roughness height
$l_{1,2}$ - parameters defining shape of prism roof
L - streamwise length of prism
$S_{1,2,3}$ - spacing dimensions between prisms
U_τ/U_1 - wall friction velocity ratio
W - cross flow width of prism
X_S - length of separated region
X_R - distance from reattachment position
δ - boundary layer thickness

3 FLOW AROUND SINGLE PRISMS

Flow around prisms is here considered in terms of; prism geometry $(\frac{W}{h}, \frac{L}{h}, \frac{l_{1,2)}}{h}$, relative prism height $(\frac{h}{\delta})$, relative positions of other prisms $\frac{(S_{1,2,3})}{h}$ and boundary layer development factors $(\frac{U_\tau}{U_1}, \frac{k}{\delta})$. Obviously a prism affects all aspects of boundary layer flow. To enable simple comparisons to be made between cases a single comparison parameter has been used by previous workers and this has usually been the drag coefficient of the prism, mainly because it is simple to measure. Drag coefficients however only relate to flow in the immediate vicinity of the prism. The present work uses centreline mean flow parameters as a basis for comparison because they are indicative of flow behaviour downstream of the prism.

3.1 h/δ

As h/δ decreases, the pressure field in front of a prism acts on a portion of the boundary layer with lower (average) inertia causing the layer to separate earlier at a larger relative distance from the prism. Earlier separation in front of the prism implies a lower flow angle for the streamline that separates from the upper leading edge of the prism. This leads to a smaller separation bubble behind the prism as is illustrated in Figure 1 for two dimensional square block data. For small h/δ the centreline recovery of the wall flow is the same in pipe and boundary layer flow, Figure 2a. However for large h/δ the outer flow eddies are modified by the prism which causes a different recovery rate, Figure 2b. In pipe flow, where large eddies cannot deflect away from the prism, this effect is more pronounced (see Schofield et al. (1984)). The behaviour of the boundary layer as a whole, downstream of reattachment, is illustrated in Figure 3 which shows that the larger the (relative) size of the prism, the larger the distortion of the boundary layer on reattachment (higher G) and the longer the recovery length required for the layer to return to undisturbed conditions.

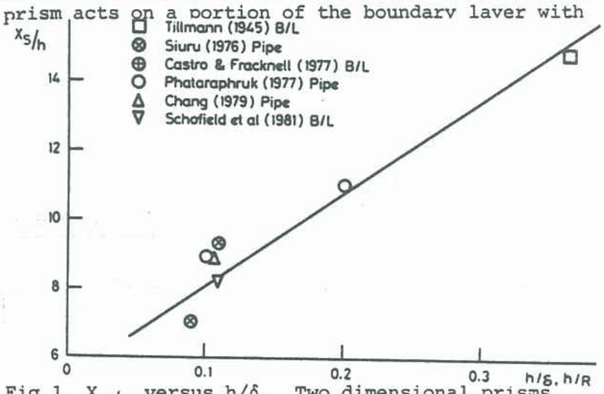

Fig 1 $X_S/_h$ versus h/δ. Two dimensional prisms.

3.2 L/h

The (relative) length of the prism affects the downstream flow through its effect on the early entrainment of the separation shear layer emanating from the leading edge of the prism. As the length of the prism increases, entrainment causes the shear layer to be

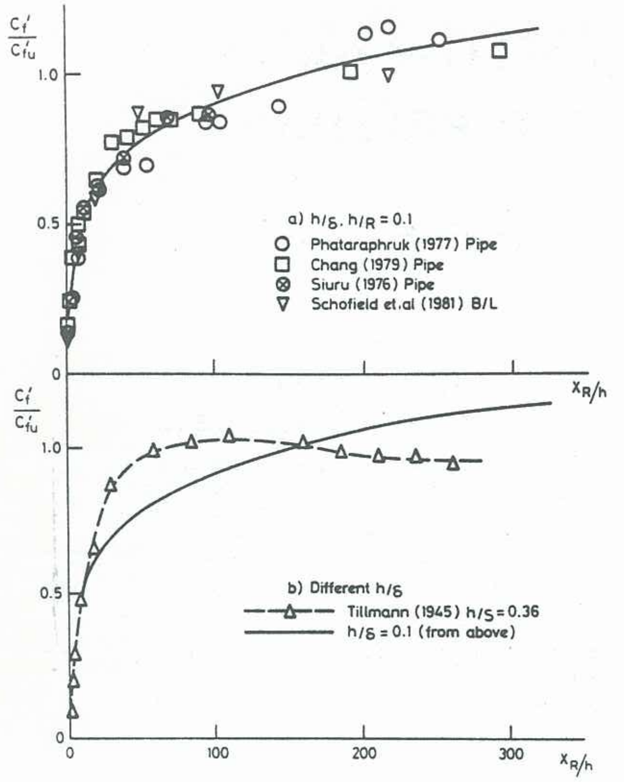

Fig 2 Skin friction recovery. Two dimensional prisms

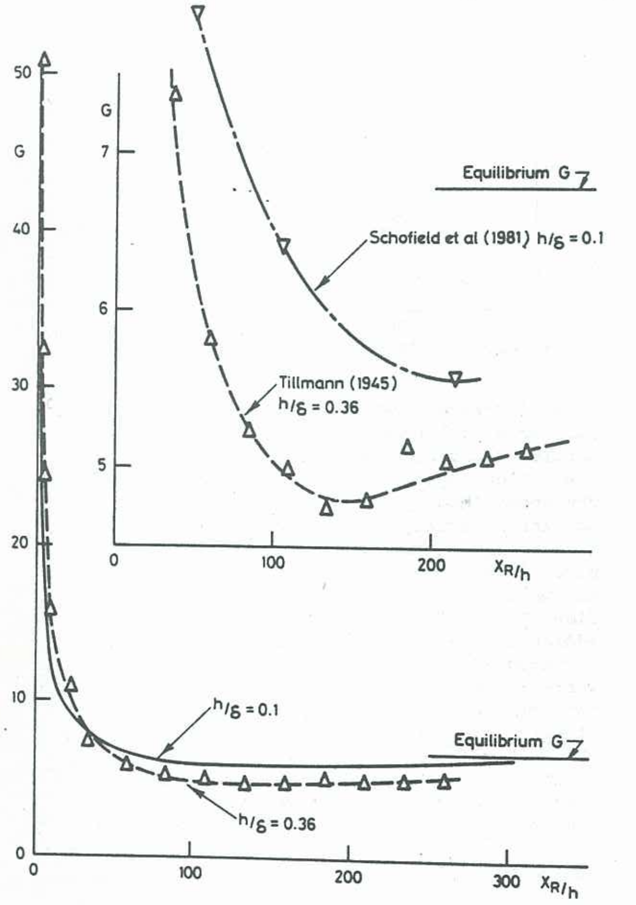

Fig 3 Boundary layer recovery. Two dimensional prisms

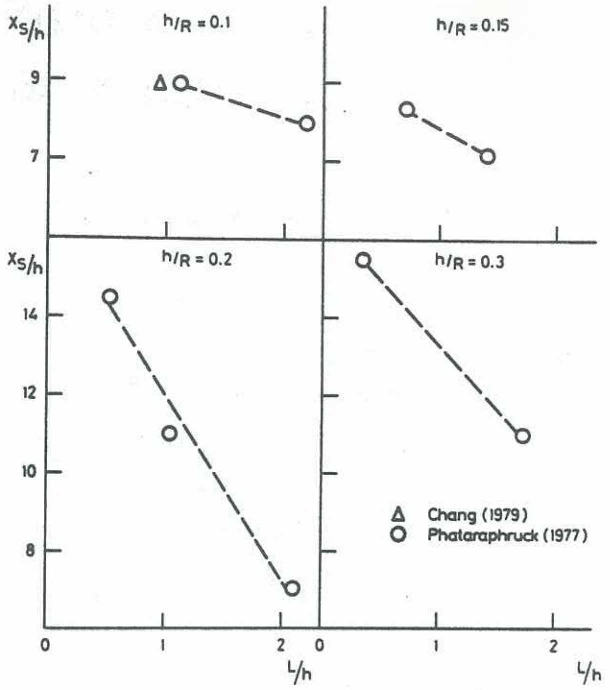

Fig 4 X_s/h versus L/h. Three dimensional prisms

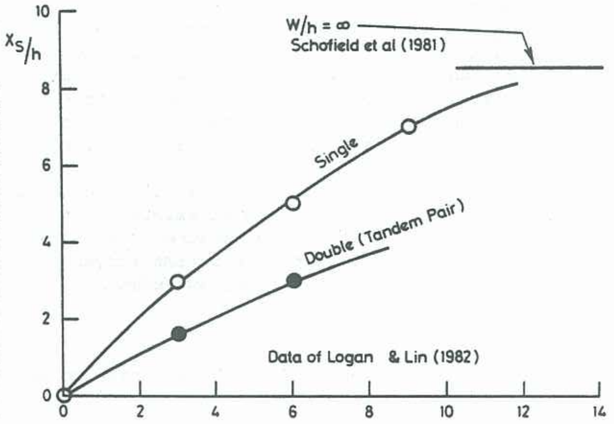

Fig 5 X_s/h versus W/h. Three dimensional prisms

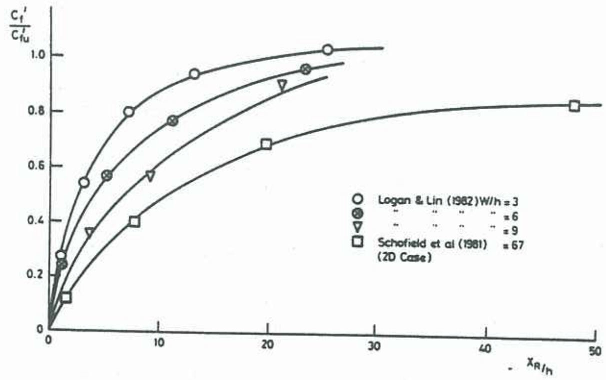

Fig 6 Skin friction recovery. Three dimensional prisms

drawn down towards the top of the prism which reduces the size of the separated region behind the prism, as shown in Figure 4. Similarly the shape of the roof of the prism affects the initial separation angle of the shear layer and also affects the early entrainment in the layer thus affecting the separation length. The large differences in the recirculating bubble size have a negligible effect on the boundary layer recovery after reattachment (see Schofield et al. (1984)).

3.3 W/h

In the two dimensional flows considered so far, boundary layer recovery after reattachment was provided by the usual turbulent exchange mechanisms in a boundary layer. For three dimensional prisms, mixing and hence recovery is greatly enhanced by large streamwise vortices generated near the prism. Vortex pairs are shed from both separated regions, in front and behind the prism (see Counihan et al. (1974)). These vortices persist in the flow far downstream and sit in the boundary layer near the wall (see Colmer (1970) and Peterka & Cermak (1977)).

The length of separated flow behind a 3D prism increases with its relative width W/h (see Figure 5). Figure 6 compares the (centreline) recovery of skin friction coefficient for a range of aspect ratios. As the aspect ratio increases, the vortices (shed from the prism) move away from the centreline with a consequent reduction in mixing on the centreline and this gives a slower recovery in wall shear. Similar results apply to outer flow mean parameters (see Schofield et al. (1984)).

3.4 U_τ/U_1 (or k/δ)

This parameter is a measure of the upstream boundary layer's susceptibility to separation by the pressure field in front of a prism and as such it affects the flow angle of the streamline separating from the roof of the prism which in turn affects the size of the rear separation region. In general it has a small effect. However for long prisms where the separation streamline is normally close to the roof of the prism, a change in U_τ/U_1 can cause this streamline to reattach to the prism roof and thereby drastically reduce the size of the separated region behind the prism (see Schofield et al. (1984)). Downstream of this reattachment, a rough wall (high U_τ/U_1) will retard boundary layer recovery.

4 FLOW AROUND MULTIPLE PRISMS

4.1 Two Prisms in Line (Tandem Pair)

If two three dimensional rectangular prisms are closely

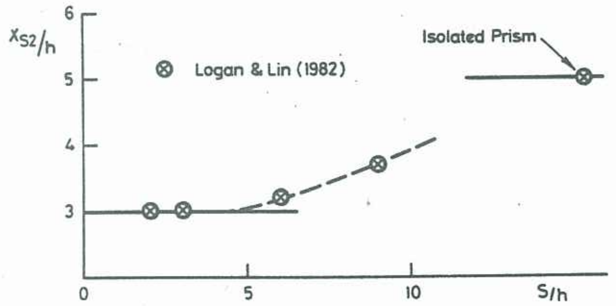

Fig 7 Separated length behind a pair of prisms in line. Three dimensional prisms

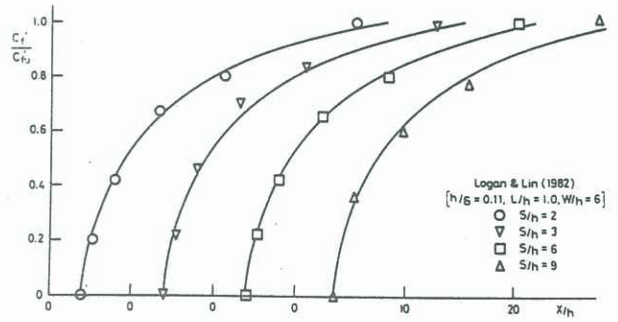

Fig 8 Skin friction recovery downstream of a pair of three dimensional prisms

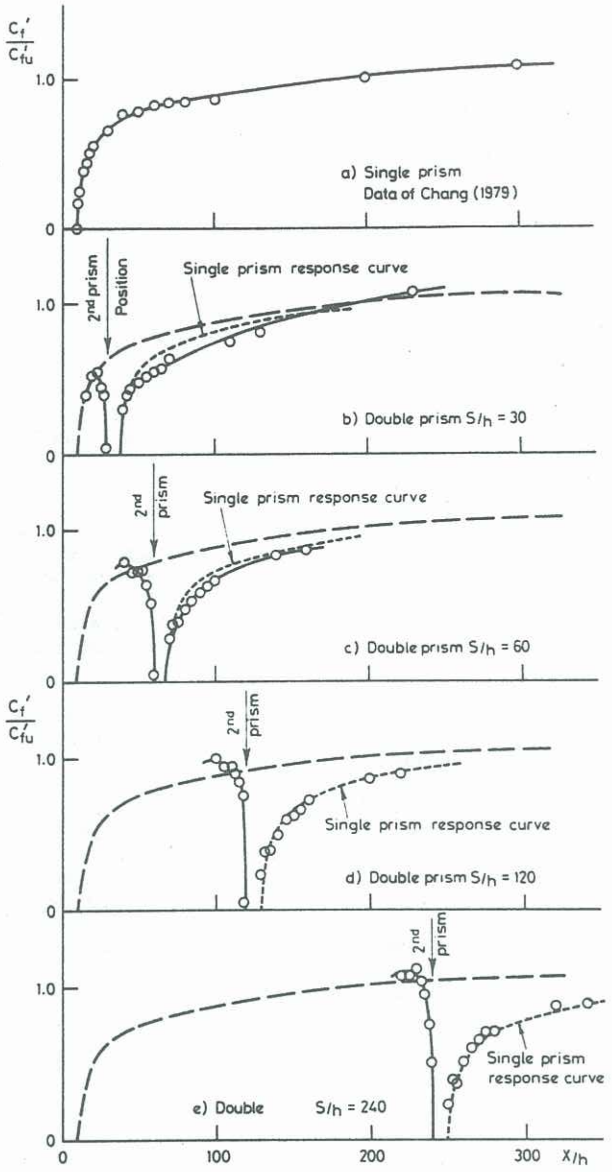

Fig 9 Skin friction recovery downstream of a pair of two dimensional prisms

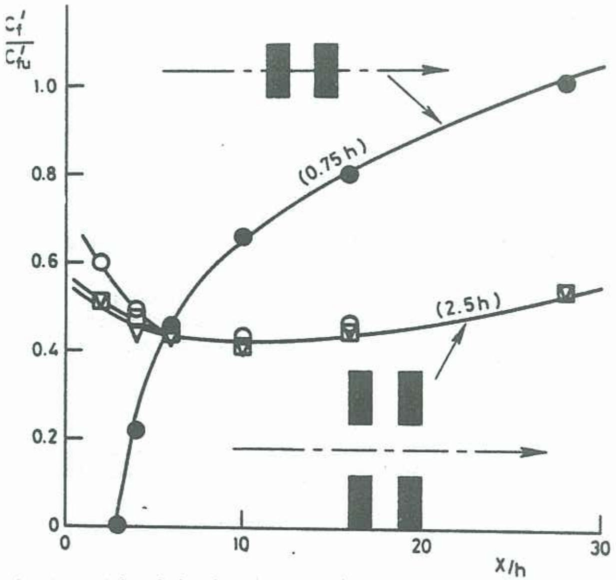

Fig 10 Skin friction recoveries for complex groups of prisms

spaced behind one another then the separation streamline from the first prism will reattach to the top of the second prism. As this streamline then leaves the second prism horizontally it forms only a small separation zone behind the rear prism. The length of this rear separation zone will not vary with increased spacing between the prisms provided the streamline remains attached to the top of the rear prism.

At moderate spacings between the two prisms the separation streamline from the leading prism attaches to the floor between the two prisms. The reattaching flow on the floor between the prisms is easily reseparated by the pressure field of the second prism which implies that the second separation zone is smaller than that for an isolated prism (see argument in 3.4). Thus as the distance between the prisms is increased the second separation zone has initially constant length and then increases slowly up to the value for an isolated prism. Data illustrating this is shown in Figure 7 (and Figure 5).

Compared with a single prism, there will be twice as many vortices shed from the two prisms into the downstream flow. However, because of the positions that these additional vortices take up in the flow they have little effect on the centreline wall recovery (see Figure 8). However, flow along streamlines away from this centreline, could be strongly affected by the additional vortices in the flow.

For the case of flow over two dimensional prisms, where flow recovery is governed by the normal turbulent transport processes in a boundary layer, there are differences in wall recovery for flow downstream of two prisms compared with that for an isolated prism. This is illustrated in Figure 9. Differences in recovery rates are obvious up to spacings between the prisms of 60h but thereafter the boundary layer has recovered sufficiently after the first prism to approximate to and respond as an undisturbed layer at the second prism. Similar results apply for outer flow parameters.

4.2 Complex Arrays of Prisms

Several complex arrays are considered in detail in Schofield et al. (1984). Due to space limitations only one case will be discussed here. Figure 10 compares the wall recovery for flow downstream of a gap between two tandem pairs (regular group of four, see Figure) with the wall recovery for centreline flow downstream of a tandem pair. The recovery rates of the wall shear for the two cases are quite different due to different distances from, the flow line being considered to the nearest vortices. For these two cases the distances are estimated to be 0.75h and 2.5h.

5 CONCLUSIONS

(i) The length of the separated region downstream of a prism increases rapidly with relative prism height.

(ii) For small h/δ the skin friction recovery for pipe and boundary layer flow is the same. For larger h/δ (>0.2) the wall recovery is different for pipe and boundary layer flow.

(iii) The relative streamwise length of a prism affects the size of the separation bubble downstream of the prism but not the recovery rate after reattachment.

(iv) The response of a boundary layer flow to a three dimensional prism is dominated by the vortices shed downstream from the prism and is more rapid than in flows over two dimensional prisms.

(v) Tandem pairs of prisms closely spaced behind one another have small (constant sized) separated regions behind them. With increasing spacing between the prisms the size of the separated region gradually increases up to the isolated prism value.

(vi) Tandem pairs of three dimensional prisms have flow recovery rates downstream of (final) reattachment that are the same as those after an isolated prism. However, tandem pairs of two dimensional prisms generate flow recoveries that vary with the spacing between the prisms (at least up to a spacing of 60h).

(vii) The flow recovery along any line downstream of a three dimensional array of prisms depends mainly on the proximity of the line to longitudinal vortices in the flow.

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