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Turbulent Flow Around Wall Mounted Prisms

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ABSTRACT

Mean velocity flows downstream of single two-dimensional prisms mounted on a wall under turbulent boundary layers, are analyzed. The recovery of the flow downstream of the perturbation caused by the prism is described in terms of the response of the inner and outer regions of the boundary layer. It is shown, that provided the data is reduced using appropriate length scales, common responses for both inner and outer regions can be demonstrated across a variety of flows. Deviations from these responses are explained in terms of distortions to the outer flow caused by the upstream prism. It is also shown that single integral parameters are unreliable indicators of the equilibrium condition of these recovering flows.

INTRODUCTION

The mean flow around a sharp edged prism is simple to analyse because at high Reynolds numbers the flow pattern around it is invariant with flow conditions or scale. However if the prism is mounted on a wall and submerged under a turbulent boundary, flow around it depends on a large number of variables (see Schofield & Logan (1983)).

The structure of turbulent boundary layers consists of large scale eddies in the outer layer rolling over fine scale turbulence generated at the wall. The two types of turbulence interact, with turbulent energy being extracted from the mean flow by the large eddies and then being passed down a cascade of eddy sizes to the smallest (Komogloroff) sized eddies in the flow. The large eddies have a length scale comparable with the boundary layer total thickness (δ) and as these eddies are most influential in determining outer flow development, it follows that parameters of a boundary layer's outer flow response and recovery to a prism should be non-dimensionalized with δ. The fine grained wall turbulence has a length scale Z which is proportional to ν/u^* on a smooth wall (see equation 1) and the height of the roughness elements on a rough wall (Schofield). Consequently recovery parameters of the wall layer downstream of a wall mounted obstacle should be non-dimensionalized by Z.

In general, previous authors have not presented results using these variables but have used instead the prism height (h). While h is probably the appropriate variable for the perturbation region in the immediate vicinity of the prism, downstream recovery should be scaled on Z and δ. Similarly the streamwise origin for the recovery phase of the flow should be at the point of flow reattachment behind the obstacle. This paper shows that by using these variables, a coherent account of flow recovery downstream of wall mounted two-dimensional prisms can be made.

WALL FLOW RECOVERY

Turbulent wall flow is characterized by the logarithmic law of the wall

$$\frac{u}{u^*} = \frac{1}{\kappa}\log_e\frac{y u^*}{\nu} + A = \frac{1}{\kappa}\log_e y/Z \qquad (1)$$

(where u is the mean velocity, u^* the friction velocity, κ and A are constants, y the distance from the wall and ν the kinematic viscosity) and can be used to determine the skin friction coefficient (Clauser 1954). After the flow reattaches downstream of a prism, equation (1) is re-established by the growth of a new wall turbulence. The vertical extent of the validity of this law (δ_i) should scale simply on Z and the distance from flow reattachment (Figure 1). The regression line

$$\log_{10}\frac{\delta_i}{Z} = 0.69\log_{10}\frac{x_R}{Z} + 0.11 \quad \left(\frac{\delta_i}{Z} \simeq \left(\frac{x_R}{Z}\right)^{2/3}\right)$$

correlates the data over nearly three decades of x_R/Z and includes both pipe and boundary layer data and a range of relative prism heights (h/δ).

The skin friction recovery downstream of reattachment is shown in Figure 2 and by using Z and x_R a wide range of data are collapsed. However this data has been restricted to flows with small upstream perturbations ($h/\delta < 0.15$). If the large outer flow eddies are distorted by the prism then the rate of energy transfer to the wall turbulence is modified and the rate of skin friction changes. As a boundary layer's deflection over a prism is unrestricted there is little difference in the skin friction recovery downstream of small and large prisms. However the vertical restraint of a pipe causes the large eddies to become elongated as they pass through the central hole formed by the prism in the pipe. As the relaxation time for these eddies is large the effects of this distortion persists downstream modifying the wall turbulence and thus the wall stress, as shown in Figure 3. These data suggest that as perturbation strength (h/δ) increases, the initial recovery in wall shear is slower and the subsequent overshoot in wall shear larger.

It should be noted that in all of these experiments the final equilibrium state was not reached. The return to equilibrium apparently requires very large flow lengths.

OUTER FLOW

At reattachment the mean velocity profile is severely distorted compared with the undisturbed equilibrium profile upstream of the prism (see Figure 4). The large strain evident in the reattaching profile relaxes outwards through the layer with distance downstream. The mean velocity difference between the relaxing and equilibrium profile is initially largest near the wall but the short time scale of wall turbulence means the return to equilibrium proceeds much more rapidly near the wall. Thus at a short distance downstream the maximum deficit in the mean profile moves away from the wall into the outer flow. The decay of the (maximum) mean deficit in the outer flow should scale with δ and this is confirmed in Figure 5 with a wide range of experimental data. The initial correlation of Figure 5a suggests a semi-logarithmic dependance and this is confirmed by the replot of data in Figure 5b.

The data in Figure 5 are for flows in which the outer eddies are not distorted ($h/\delta < 0.16$). Data for other flows are given in Figure 6. As before the results for a large prism in a boundary layer (Figure 6a) are little different from the small prism results. However in pipes, the flow distortion caused by large prisms significantly modifies the downstream response of the outer flow (Figure 6b).

There is one other case to be considered and that is the recovery downstream of an obstacle so small that the strain in the flow is obliterated by the wall turbulence before it is transmitted into the outer flow. The profiles for such a case are shown in Figure 7 and the decay in the deficit is shown in Figure 6c. This decay rate is obviously quite different to the

Figure 6c. This decay rate is obviously quite different to the previous cases.

OVERALL FLOW RESPONSE

The mean velocity profiles in Figure 8 show that the return of a mean profile to its equilibrium distribution is not monotonic. As the outer profile approaches an equilibrium distribution, the flow near the wall continues to accelerate and moves the wall profile past the equilibrium distribution. Such behaviour is implied by the skin friction distribution overshooting its equilibrium value in Figures 2 and 3.

The most common method for judging the equilibrium condition of a two-dimensional boundary layer is to evaluate Clauser's (1954) integral shape parameter

$$G = \int_0^1 \left[\frac{U_1 - u}{u^*}\right]^2 d\left(\frac{y}{\delta}\right) \Big/ \int_0^1 \left[\frac{U_1 - u}{u^*}\right] d\left(\frac{y}{\delta}\right)$$

where U_1 is the free stream velocity. G has a value near 6.8 for an equilibrium boundary layer profile. Although it is obviously attractive to be able to use a single parameter to judge the degree of departure from equilibrium of a layer, data presented above, show that for flows downstream of a wall mounted prism, distributions in the value of G require careful interpretation. As seen in Figure 8 the profiles adjust unevenly with inner and outer regions attaining the equilibrium distribution at different streamwise distances. This combined with the large overshooting in the wall profile means that an equilibrium value of G does not necessarily mean the layer has reached equilibrium. For instance the profile at $x_R/R = 7.1$ (where R is pipe radius) in Figure 8b has a value of G near 6.8 but the profile shape is far from equilibrium.

Figure 9 plots the variations of G for a number of boundary layers. Here δ_R has been used as a non-dimensionalizing parameter because most of the long term adjustment of profile shape occurs in the outer flow region of the layer. Using these parameters, the data of Petryk & Brundsett (1967) and Tillmann (1945) form a progressive ordered set which was not achieved by Bradshaw & Wong (1972) using parameters appropriate to the perturbation region (h , x where x is streamwise distance from the prism). The data of Figure 9 show a mild dependence on relative prism height with the minimum value of G decreasing and occurring slightly later in the recovery process. As before similar but more pronounced variation occurs in pipe flow (Figure 10). Here with increasing prism height there is a large reduction in the minimum value of G and also the minimum occurs earlier in the relaxation process.

CONCLUSIONS

The analysis of mean flow data downstream of a two-dimensional prism in a turbulent boundary layer leads to the following conclusions;

(i) the depth of new wall turbulence generated after reattachment grows at a rate proportional to approximately $x^{2/3}$,

(ii) distributions of skin friction downstream of reattachment overshoot the upstream equilibrium value. The return to a final equilibrium state apparently requires very long development distances and has yet to be observed;

(iii) the large mean strain near the wall caused by a wall mounted prism is rapidly relieved and transferred into the outer layer by turbulent mixing. Subsequent modifications to the outer profile proceed slowly due to the long time constant of the outer turbulence,

(iv) the maximum difference in mean velocity between the perturbed and equilibrium profiles, decays in a semi-logarithmic rate with streamwise distance. This rate is reduced for the case of a large prism in a pipe. For the case of a very small prism where the profile recovery is accomplished in the wall layer before the strain is transferred to the outer flow, the recovery rate is very fast and does not follow a semi-logarithmic distribution,

(v) because the rate of return to equilibrium of the inner and outer regions of a perturbed layer are grossly unequal and in addition the wall flow overshoots its equilibrium distribution, a single integral profile parameter such as Clauser's G is an unreliable measure of the state of equilibrium of these flows.

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FIGURES

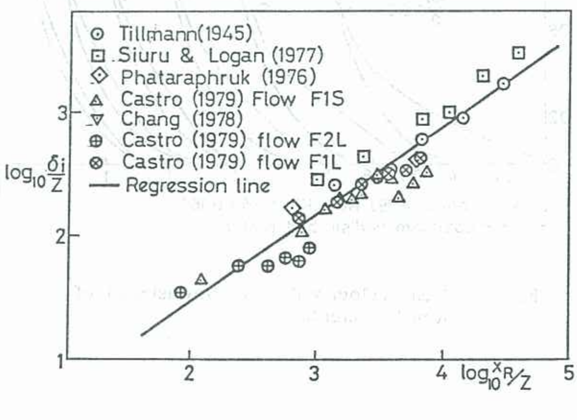


Fig 1. Growth of Internal Wall Layer.

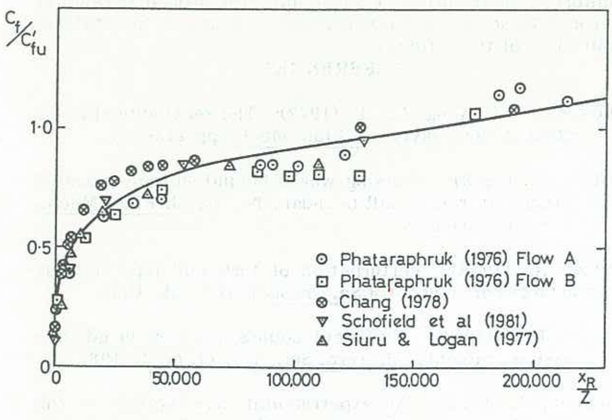


Fig 2. Skin Friction Recovery. (Small h/δ).

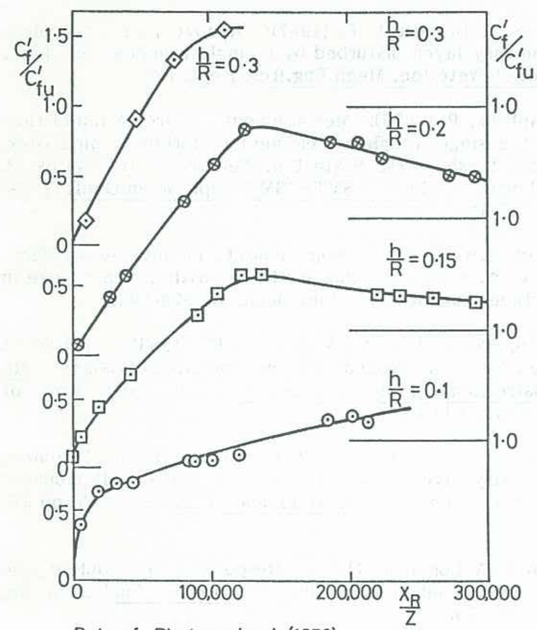


Fig 3. Skin Friction Recovery in a Pipe.

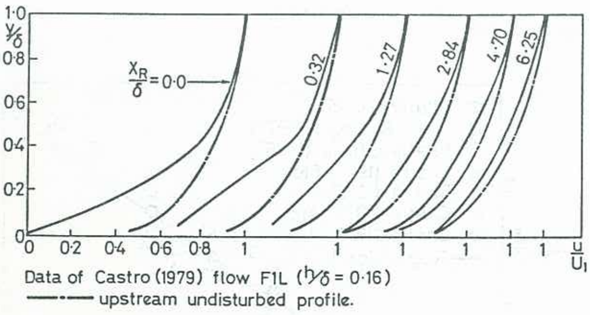


Fig 4. Mean Velocity Profiles Downstream of Reattachment.

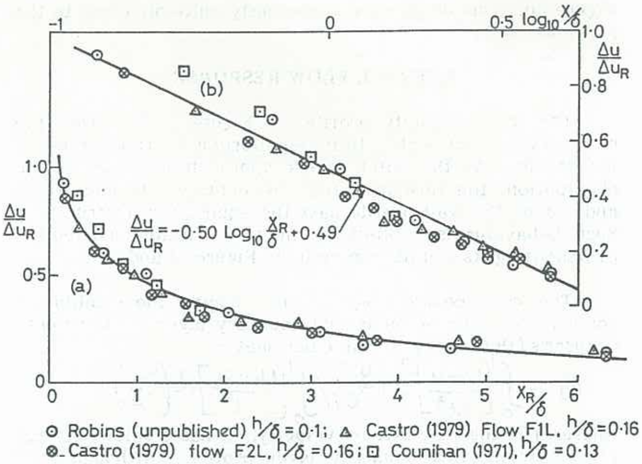


Fig 5. Maximum Deficit in Mean Velocity. (Small h/δ).

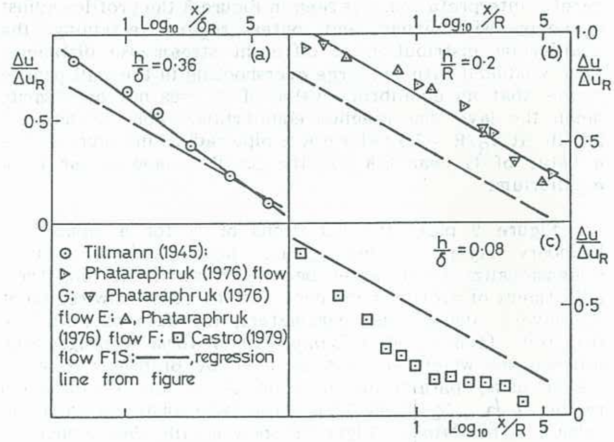


Fig 6. Maximum Deficit in Mean Velocity.

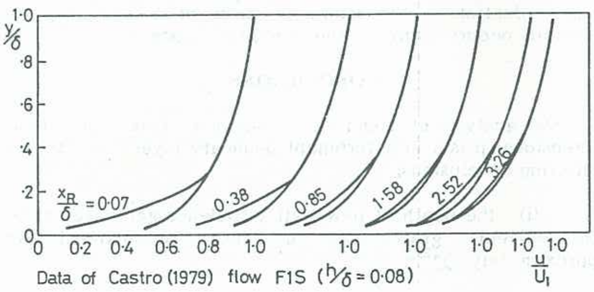
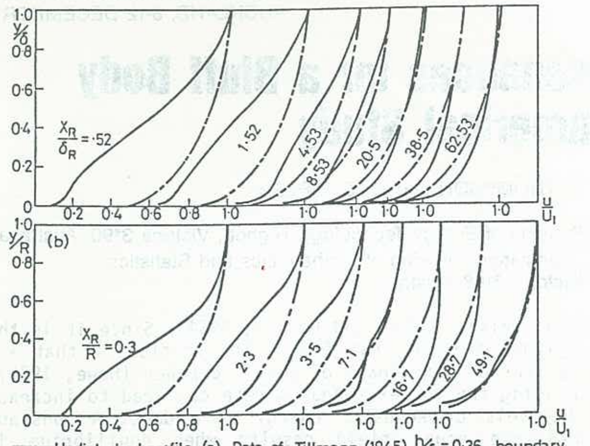


Fig 7. Mean Velocity Profiles Downstream of Reattachment. (Very small h/δ).



——·—Undisturbed profile (a) Data of Tillmann (1945). h/δ = 0·36, boundary layer flow (b) Data of Phataraphruk (1976) Flow E. h/R = 0·20 pipe flow

Fig 8. Mean Velocity Profiles Downstream of Reattachment. (Large h/δ).

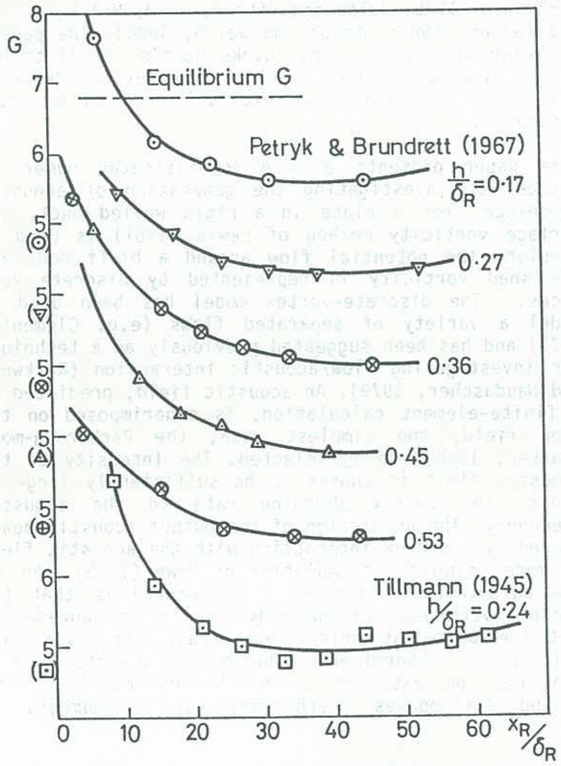


Fig 9. Variation of G for Boundary Layer Flow.

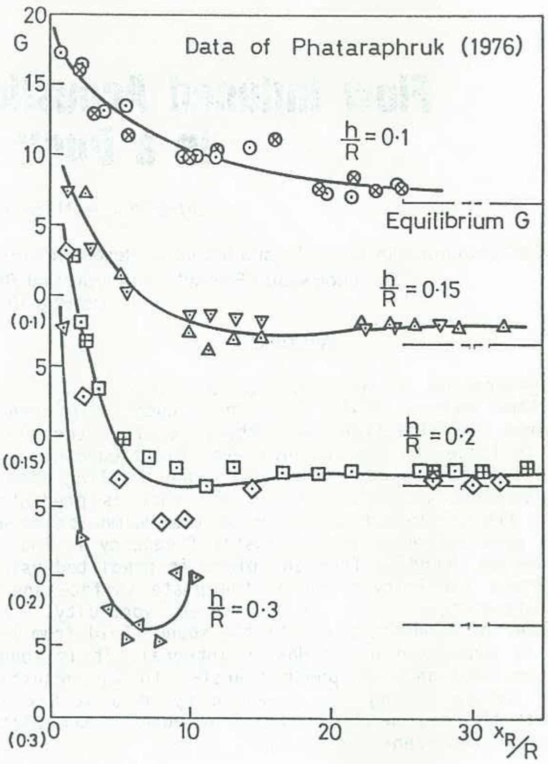


Fig 10. Variation of G for Pipe Flow.