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DRAG CHARACTERISTICS OF SHARP-EDGED BODIES IN TURBULENT BOUNDARY LAYER FLOW WITH NEGATIVE PRESSURE GRADIENT

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SUMMARY Available data on form drag of two dimensional and three dimensional rectangular blocks placed in a turbulent boundary layer under a negative pressure gradient are analysed. It has been found that the drag coefficient (defined with respect to the shear velocity) in flows with negative pressure gradient is smaller than that for flows with zero pressure gradient. Empirical relations for the drag coefficient in terms of aspect ratio, opening ratio, thickness to height ratio and h/y' have been developed.

1 INTRODUCTION

The drag characteristics of two-dimensional fences placed in a turbulent boundary layer under zero pressure gradient have been studied by Plate (1964), Good and Joubert (1960), Ranga Raju and Garde (1970) and Ranga Raju et. al. (1976). Sakamoto et. al. (1982) have studied the drag characteristics of cubes and square cylinders placed in boundary layer flow. The influence of three-dimensionality on the drag of fences has recently been studied by Sakamoto and Arie (1983). The effect of the streamwise thickness of the fence (when it is not of zero thickness) as well as that of the pressure gradient on the drag of those bluff bodies has not yet been studied in detail. Extensive data on both these aspects were collected a few years ago by Meyer (1979) and these have been analysed in this paper. It may be pointed out that the results would be particularly valuable in analysing the flow past spurs located on river banks, since these structures are exposed to boundary layer flow with a negative pressure gradient.

2 EXPERIMENTAL DATA

The experiments were carried out by Meyer (1979) in an air duct 700 mm wide and 7.80 m long and having smooth walls. The depth of the duct was adjustable and was varied from 60 mm to 210 mm. The bluff bodies were placed on the floor at a station 4.40 m from the entrance and the drag force was measured directly using a force transducer. The above station was one at which the turbulent boundary layer was fully established. The wall shear stress prior to the placement of the bodies was obtained with the help of a Preston tube. The range of geometrical parameters of the rectangular blocks used in these experiments is as given in Table 1. Here h is the height of the body, t its thickness, b its width and B the tunnel width. The parameter B could also be viewed as the centre to centre spacing in the lateral direction if a series of blocks is placed across the width. Also δ is the thickness of the undisturbed boundary layer. A constant block height of 1 cm was used in these experiments.

Table I

Range of Data Used

t/h	b/B	b/h	δ/h
0-2.0	0.10-1.00	1.90-5.80	6.0-21.0

The dimensionless pressure gradient term P defined as

$$P = \frac{\nu}{\rho U_o^3} \frac{dp}{dx} \qquad (1)$$

varied from 8×10^{-9} to 3.4×10^{-8} in case of undisturbed flow for these data. Here dp/dx is the longitudinal pressure gradient, ν is the kinematic viscosity, ρ is the mass density and U_o the centre line velocity.

3 ANALYSIS OF DATA

Ranga Raju et. al. (1976) have shown that the drag coefficient of two-dimensional fences placed in a turbulent boundary layer can be expressed by the relation

$$C_o^* = f\ (h/y') \qquad (2)$$

Here C_o^* is the drag coefficient corrected for blockage and defined as

$$C_o^* = \frac{2F_D}{bh\rho u_*^2} \qquad (3)$$

and y' is the roughness parameter defined by the logarithmic law

$$\frac{u}{u_*} = \frac{1}{k} \ln \frac{y}{y'} \qquad (4)$$

In the above equations F_D is the drag force on the body, u_* the shear velocity of the undisturbed flow, k is Karman's constant and u the velocity at a distance y from the boundary. It is significant that Eq. (2) was found to be valid even for $h/\delta < 1.0$, implying that it is only the velocity profile in the inner region which affects the drag coefficient; in case the drag coefficient were affected by the velocity profile in the outer region, one would have expected u_*/U_o also to affect C_o^*, which was not the case. Interestingly, Sakamoto et. al. (1982), found the foregoing conclusions to be valid upto $h/\delta \approx 1.0$ even for cubes. Consequently, one may write the functional relation for three-dimensional rectangular blocks as

$$C_o^* = f\ (h/y',\ t/h,\ b/B,\ b/h,\ P) \qquad (5)$$

The data have been analysed in accordance with Eq. (5)

3.1 Two-Dimensional Blocks

In case of two-dimensional blocks, b/B is equal to unity and hence Eq.(5) may be simplified to

$$C_o^* = f\ (h/y', t/h, P) \qquad (6)$$

The measured drag force was corrected for blockage using the relations of Ranga Raju and Vijaya Singh (1976) and hence C_o^* computed. Since the boundary in case of Meyer's study was smooth, y' was determined from the equation

$$y' = 0.128\ \nu/u_* \qquad (7)$$

The data are plotted in the form of C_o^* vs h/y' in Fig.1 on which the relationship for two-dimensional

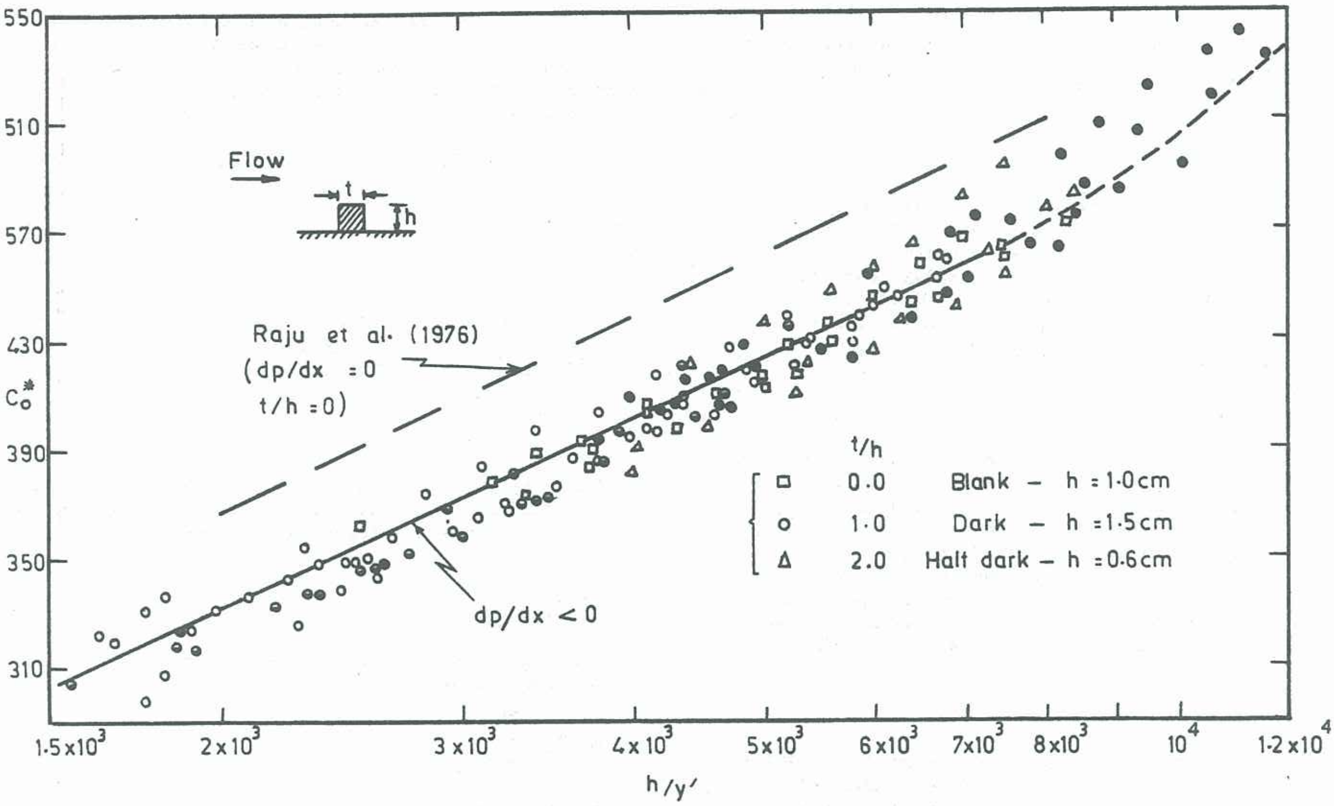

Figure 1 Relation for Drag Coefficient of Two-Dimensional Rectangular Blocks

fences in flows with zero pressure gradient is also shown. It is seen that the drag coefficients in case of flows with negative pressure gradient are smaller than those for flows with zero pressure gradient; however, the scatter of data is not systematic with variation in the value of P and hence a mean line has been drawn for the data covering the range of P from 8×10^{-9} to 3.4×10^{-8}. Further, the parameter t/h does not seem to have any effect on C_o^* in the range $0 \leqslant t/h \leqslant 2.0$.

3.2 Three-Dimensional Blocks

Since the blockage in case of three-dimensional blocks was very small, no corrections were applied for blockage in case of these data. A typical plot of C_o^* vs h/y' for some of the three-dimensional blocks is shown in Fig.2. Also shown on this figure is the relation between these parameters for two-dimensional blocks. It is seen that the values of C_o^* (for a given value of h/y') decrease consistently with decrease in b/B. Further the line described by the data for a given set of values of b/B and b/h is parallel to that obtained for two-dimensional blocks. This suggests that there is a constant value of correction ΔC for each set of b/B and b/h values, which, when applied, would bring these data along with the data for two-dimensional blocks. These corrections ΔC were determined for all the blocks with the help of figures similar to Fig.2 and the variation of ΔC with b/B, b/h and t/h is shown in Figs. 3 and 4. As expected, ΔC tends to zero as b/B tends to unity in all cases. A physical explanation for the observed effects of the parameters b/h and t/h on the drag coefficient can only be offered when detailed measurements concerning the separation zones are available. It may be pointed out that, in the case of strips of negligible thickness, Sakamoto and Arie (1983) found the drag coefficient to be the least at a value of b/h equal to 5.0. Their studies covered a wide range of b/h - from 0.5 to 10.0. Since the range of the present data is limited, it is

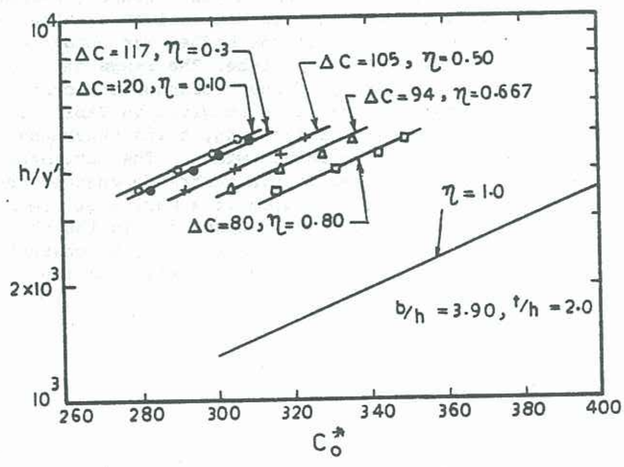

Figure 2 Diagram illustrating Effect of Three-Dimensionality on Drag Coefficient

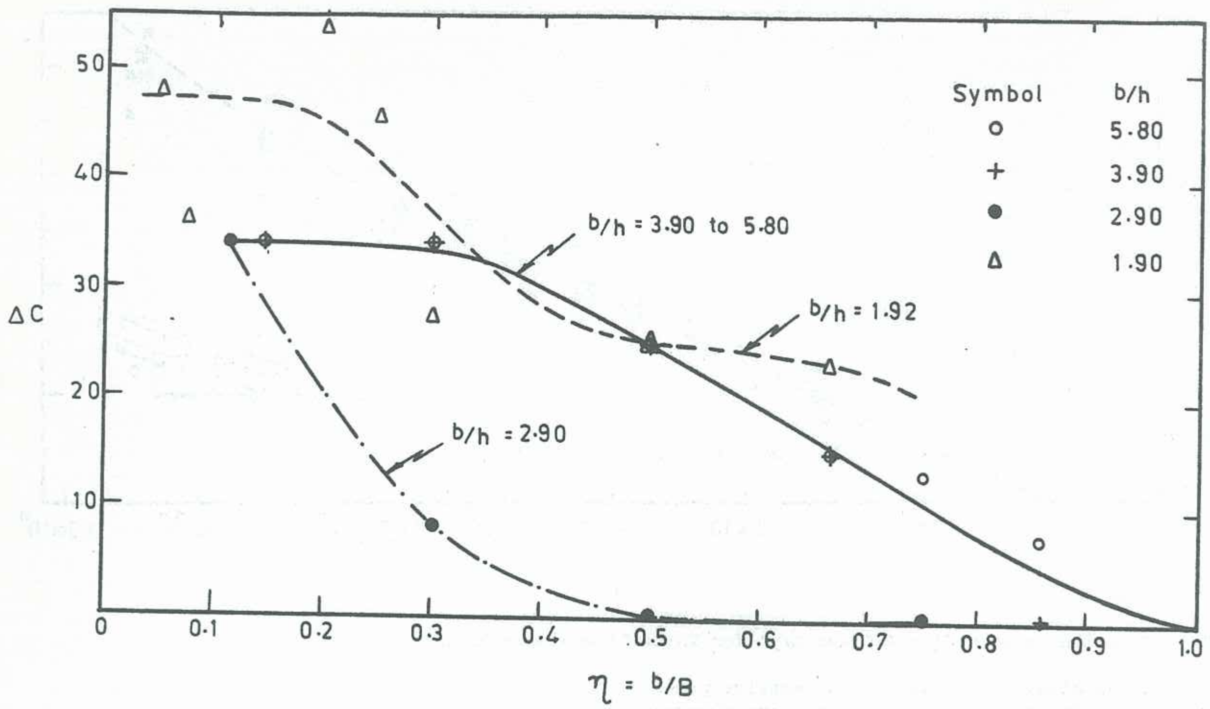

Figure 3 Variation of ΔC with t/B and b/h for t/h = 1.0.

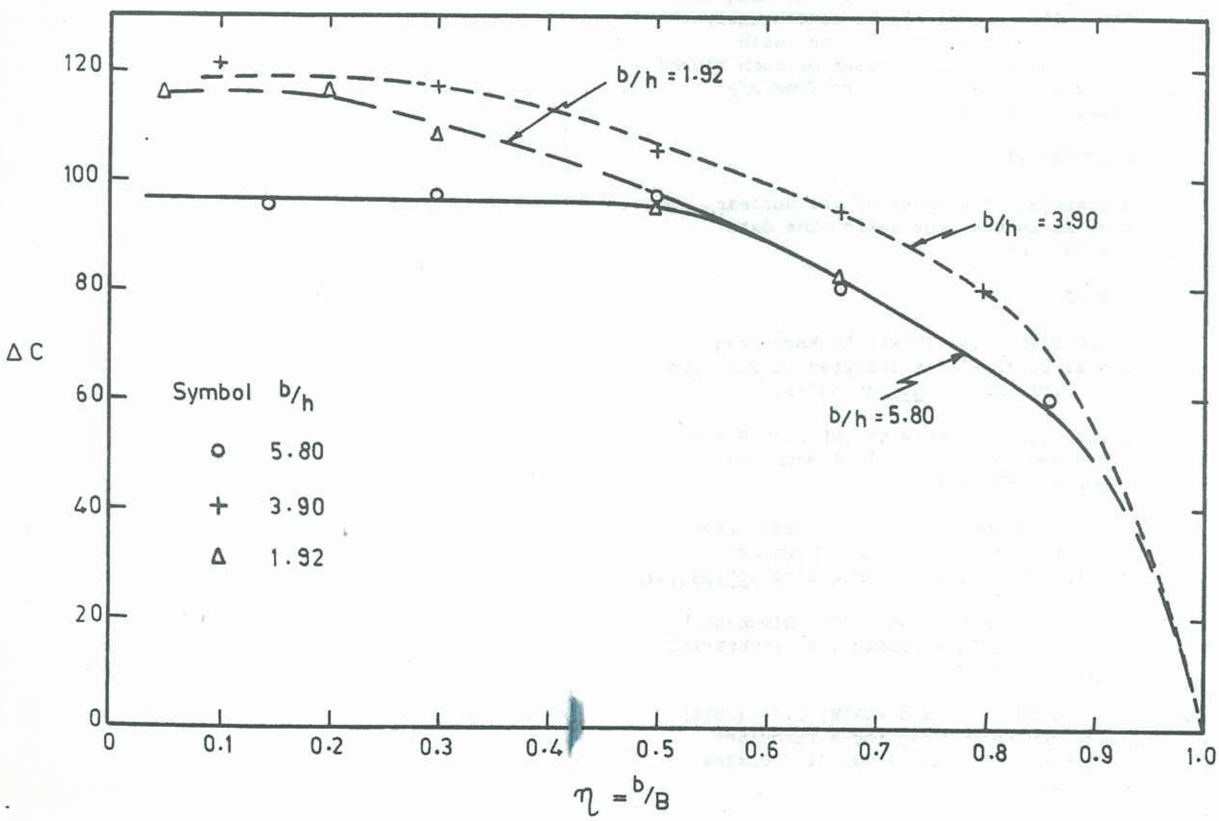

Figure 4 Variation of ΔC with b/B and b/h for t/h = 2.0.

hard to say whether there is a similar trend in case of strips of finite thickness placed in boundary layer flow with a negative pressure gradient.

Using the values of ΔC read from Figs. 3 and 4, a plot of ($C_0^* + \Delta C$) versus h/y' has been prepared for all the data on three-dimensional blocks;see Fig. 5. The data agree with the relation for two-dimensional blocks showing only a small amount of scatter. As such, one may use Figs. 1, 3 and 4 to calculate the drag coefficient of such blocks.

4 CONCLUSIONS

Data on form drag of two and three-dimensional rectangular blocks placed in a turbulent boundary layer under negative pressure gradient have been analysed. It is seen that the drag coefficient of

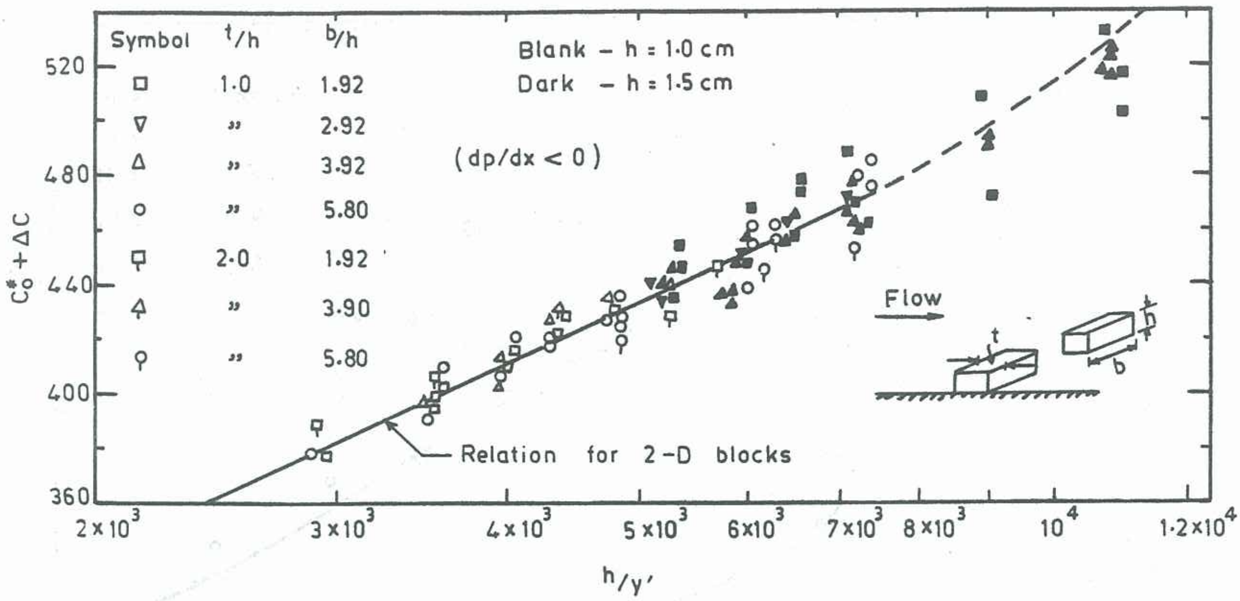

Figure 5 Relation between $C_o^* + \Delta C$ and h/y' for Three-Dimensional Blocks

two-dimensional blocks in flows with a negative pressure gradient is smaller than that for zero pressure gradient. The parameter t/h does not have any effect on the drag coefficient of two-dimensional blocks in the range of $0 \leqslant t/h \leqslant 2.0$. The drag coefficient of three-dimensional blocks consistently decreases from its two-dimensional value with decrease in b/B. The drag coefficient of such blocks is dependent on b/B, b/h and t/h apart from h/y' as shown in Figs. 3,4 and 5.

5 ACKNOWLEDGEMENT

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