The drag coefficient of the cylinder integrated from the measurements of the pressure on the surface is given in Fig. 12. The drag coefficient is defined as

\[ C_D = \frac{1}{U_0^2} \int_0^h \int_0^\frac{h}{8} \frac{p - p_0}{\frac{1}{2} \rho U_0^2} \cos \theta d\theta dh \] (17)

It can be seen in this figure that the results exhibit the same features as those of the cube shown in Fig. 5, i.e., the drag coefficient of the cylinders is also dependent on \( U_0 / U_0 \) within the range of \( h/8 \) which is less than about 1.0. The drag coefficient plotted on a log-log sheet shows a linear trend within the range of \( h/8 \) which is less than about 0.2 where the flow is in a different form. Probably, the drag coefficient of the cylinders is also dependent on \( U_0 / U_0 \) and is uniquely related to \( h/8 \).

The pressure drag of these bluff bodies was experimentally correlated with the thickness and wall shear stress of the boundary layer at the location of the bodies which would be measured if they were absent. It was found that the drag coefficient in the form of \( \log_{10} C_D \) can be expressed as a linear function of \( \log_{10}(h/8) \) with the gradient depending on the parameter \( U_0 / U_0 \) in the range \( h/8 \leq 1.0 \). Further, the drag coefficient of these bluff bodies in this range as defined by

\[ C_D = D/(\sqrt{2} \rho U_0^2 h^2) \] (18)

Fig. 13 Relation between \( C_D \) and \( h/8 \) for a vertical circular cylinder. For further information, see the caption of Fig. 7.

parallel to the plane boundary, may be judged to be well conserved in the neighborhood of the centerline of the front face in this range. However, a horseshoe vortex is dominant in the range of \( y/h \) less than about 0.2, and the negative suction pressure at the top of the cylinder prevails in the range of \( y/h \) larger than about 0.7.

It is worth noting that, against the height in this range, the slope of the straight lines curve irrespective of both the body height and the boundary layer characteristics. Further, the pressure distributions along the centerline of the front face show a good agreement with the dynamic pressure in an undisturbed boundary layer at the location of the bluff bodies, except in the two distinct ranges of \( y/h \) which are less than about 0.2 where the flow is influenced by the horseshoe vortex and larger than about 0.7 where the prevailing flow is influenced by the suction pressure along the top surface of the bluff body.

The drag coefficient \( C_D \) is dependent on \( U_0 / U_0 \) and uniquely related to \( h/8 \). A functional relationship between \( C_D \) and \( h/8 \) is found for the case of the cubes. However, it is difficult to find a similar functional relationship between \( C_D \) and \( h/8 \) from the present results because the data is not sufficient for the vertical circular cylinders.

References


DISCUSSION

E. Plate

The authors of the above-mentioned paper are to be congratulated on the excellent experimental data which they have obtained. The extensive experimentation took a great deal of patience and a long term program. The results are a useful addition to the still rather limited literature on the resistance of three-dimensional bodies immersed in turbulent boundary layers. In addition, the writer believes that the study is a valuable contribution to the theory for modelling of wind forces on structures.

Present technique of wind tunnel modelling consists of establishing a boundary layer along the wind tunnel floor with a distribution of mean velocity obeying a power law with an
exponent which is the same in model and prototype (for example Plate, 2). It is assumed that under this condition the nondimensional forces, as expressed by the drag and lift coefficients, are the same in model and prototype, provided the Reynolds number based on the building height exceeds in the model a value of about $10^4$, and provided that the corners of the building are sharp-edged. This modelling law is independent of the boundary layer height $\delta$, supposedly as long as the structure is embedded in the boundary layer. An alternate way of stating this modelling law is to say that only the parameters of the well-known “inner law,” or “law of the wall” of the velocity distribution are important for modelling purposes, a statement which can be expressed differently as saying that the ratio of $h/z_0$ is the same, where $h$ is the building height and $z_0$ is the roughness height, which for a smooth wall is $z_0 = n/u$. The argument is completed by assuming that a unique relationship exists between the exponent of the power law and a suitably dimensionless ratio $z_0/L$ where $L$ is a characteristic length of the rough boundary.

The question is unresolved of how thick $\delta$ has to be in order to obtain independence of $h/\delta$. The disturbing possibility exists that this is valid only over the height of the validity of the “inner law” of the velocity distribution, which is only about $0.0360\,\delta$ and thus makes it very difficult to model high buildings at a reasonable scale. For the case of a fence Ranga Raju et al. [4] have shown that inner law scaling is valid up to values of $h/\delta = 1$, but experiments of Castro and Robins (1) have revealed a more complex relationship between pressure distribution and approach velocity profile. It is therefore most gratifying that the excellent results of the authors establish firmly that at least for the drag coefficient of cubical bodies in smooth surface boundary layers “inner law” scaling is valid also up to $h/\delta = 1$ as is evident in equation (12), and in Fig. 7. The writer would be most interested in hearing if the authors found this scaling confirmed also for rough boundaries.

Additional References


Authors’ Closure

It is within only about 15 percent at most of $\delta$, the thickness of the boundary layer, that the inner law holds in the distribution of velocity in a turbulent boundary layer developing along a plane wall. However, $C_{D_2}$, the drag coefficient, of the two- or the three-dimensional body immersed in a turbulent boundary layer is represented, in a range up to about $h/\delta = 1.0$, by the same form of $hu_\tau/\nu$ as the case in which the distribution of velocity of an inner layer is represented by the form of $hu_\tau/\nu$. The reason for it remains not so clear except that the result from the following is considered to provide a support that the coefficient of drag of a body measured by the present experiment by a function of $hu_\tau/\nu$ in a range up to about $h/\delta = 1.0$. Namely, attached Fig. 1 shows the coefficient, $\bar{\theta}_h = \bar{\theta}/(\sqrt{\nu_\tau})$, of the mean dynamic pressure given by the following and made dimensionless by $\sqrt{\nu_\tau}$:

$$\bar{\theta} = \frac{1}{h} \int_0^h \frac{1}{2} \rho u^2 dy$$

similarly to the case of $C_{D_2}$, in a range $y = 0 \sim h$, in an undisturbed boundary layer at the location of a body which is considered as being governed by the drag of the body; similarly to $C_{D_2}$, independently of $u/U_0$, in a range up to $h/\delta = 1.0$, $\bar{\theta}_h$ is represented by a function of only $hu_\tau/\nu$.

Measurements have not been made of drag of a body on a rough wall, but $\bar{\theta}_h$, the coefficient of mean dynamic pressure, in a boundary layer developing on a rough wall is also considered to be represented by a function of $hu_\tau/\nu$. Similarly to the case using a smooth wall. Accordingly, $C_{D_2}$ of a body on a rough wall is conjectured to be represented also by a function of $hu_\tau/\nu$ in a range up to about $h/\delta = 1.0$. 

Fig. 1

![Graphical representation of the data](image-url)