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By R. W. F. Gould
Aerodynamics Division, N.P.L.

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Summary.

Measurements described show that Maskell's wake blockage corrections apply to rectangular plates normal to the flow, over the range $1/3 \geqslant h/b \geqslant 3$ tested, whether the plates are mounted on the tunnel axis or adjacent to a wall. Only small non-linear effects were found even when the corrections approached 100 per cent.

Blockage correction formula are developed for use when two models are present in the working section at the same time (but each outside the wake of the other).

The method of determining the required blockage factors is described with examples from measurements on flat plates mounted normal to a wall and on lattice models.

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*Replaces N.P.L. Aero Report 1290—A.R.C. 31 007.

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1. *Introduction.*

Maskell's theory of wake blockage in closed tunnels[1] was originally intended for use with aircraft models. However, it appeared at a time when interest was growing rapidly in the testing of bluff models representing building structures and was therefore of vital concern in non-aeronautical testing.

The work described in this paper began as simple experiments to find the limitations of the new theory when applied to the large blockages arising in the testing of bluff models, particularly those mounted on the floor. The results of the initial tests proved very encouraging and the work was extended to cover interference effects between more than one bluff mode in the same tunnel. The only tunnel at NPL having a suitable balance combined with a working section of adequate length was the 7′ × 7′ tunnel, and this was used for most of the measurements. Some confirmatory experiments were undertaken in the 13′ × 9′ tunnel.

This report describes a linked series of experiments which present a fairly coherent picture of one type of interference effect among the many still needing investigation.

2. *Preliminary Measurements.*

3.1. *Theoretical Background.*

Maskell[1] has derived expressions for the correction of force and pressure coefficients measured in closed wind tunnels on bluff models subject to separated flow. For symmetrical models, normal to the wind direction, (such as flat plates) the relationships given are

$$\frac{C_D}{C_{D_c}} = \frac{q_c}{q} = \frac{1-C_p}{1-C_{p_c}} = 1+n\,C_D\,S/C \qquad (1)$$

where the subscript c refers to corrected values, C_D and C_p are coefficients of drag and pressure, the dynamic pressure q far upstream becomes a value q_c in the plane of the plate due to blockage, S is the frontal area of the plate and C the cross-sectional area of the tunnel.

The theoretical value of the blockage factor n is $-1/C_{p_{bc}}$, where $C_{p_{bc}}$ is the corrected value of the separation pressure coefficient of the model (which happens to be equal to mean base pressure coefficient in the case of a flat plate normal to the wind).

If we rewrite the blockage term $n\,C_D\dfrac{S}{C}$ as $\dfrac{nD}{qC}$ then, for a given approach dynamic head q, the blockage effect varies directly with the drag per unit area of tunnel section. Furthermore, since these expressions were derived without the use of mathematical devices subject to image interference from walls (e.g., sources) there would appear to be no inbuilt limitation on the position of the model.

The preliminary experiments were devised to check the value of the blockage factor n, and its variation over a wide range of $\dfrac{S}{C}$ values for the extreme positions represented by axially-mounted and wall-mounted models.

2.2. *Experimental Method.*

The 7′ × 7′ tunnel at NPL has a balance midway along its 24 ft (7·31 m) long working section. The corner fillets to the working sections decrease slightly in size with distance downstream to compensate for boundary layer growth, and the sectional area in the plane of the balance is exactly 45 sq. ft (4.18 m^2). For the purposes of the present investigation it was necessary to check and, in consequence, modify the windspeed measurement system as described in Appendix A.

The models used in these measurements were plates of 7/8 in. (22 mm) plywood having sides in the ratio exactly 2:1. The reason for this choice of side ratio was that in tests on plates normal to the wind Fail, Lawford and Eyre[2] had showed that the base pressure for 2:1 plates was very close to that for square plates. Provided therefore that the tunnel boundary layers were thin, it seemed reasonable to argue that a plate with $b = 2h$ mounted within 1/8 in. (3 mm) of the roof (so that the plate and its image in the roof were equivalent in some respects to a square plate in midstream) would be almost unaffected by the slight leakage through the gap between the plate and the roof.

Initially a 22 in. × 44 in. (55·9 × 111·8 cm) plate was mounted on the balance normal to the wind in the centre of the tunnel. The relative proportions of the plate and balance support guards within the tunnel are shown in Fig. 1.

The drag was measured at 90 ft/s (27·4 m/s) in this condition and then measured again with dummy support guards mounted on the floor. The difference between these readings (about 3 per cent) was subtracted from the first reading to give a close approximation to the drag of the centrally mounted plate in the absence of any support interference. The plate size was reduced to 10 in. × 20 in. (25·4 × 50·8 cm) in stages, while maintaining the ratio between the sides, and the same drag measurement procedure was followed at each stage.

Next a 22 in. × 44 in. (55.9 × 111·8 cm) plate was mounted on the balance normal to the wind and with a 1/8 in. clearance between the plate and the roof. This time the thin steel plate supports were entirely in the wake immediately behind the board and no support corrections were necessary. This plate was also progressively reduced in size and a series of drag measurements were made.

2.3. *Discussion of Results of Preliminary Measurements.*

Figs. 2 and 3 show the values of the measured drag coefficients plotted against the blockage parameter $C_D S/C$ (evaluated more simply as D/qC). Although straight lines could be fitted to the results without serious deviation, careful analysis showed that the points were better represented by quadratic curves over the range of measurements. The expressions suggested are:

For centrally-mounted plates with $0 < C_D S/C \leqslant 0{\cdot}3$

$$C_D = 1{\cdot}163\left[1+2{\cdot}81\, C_D\frac{S}{C}-0{\cdot}96\left(C_D\frac{S}{C}\right)^2\right] \quad (2)$$

and for wall-mounted plates

$$C_D = 1{\cdot}132\left[1+2{\cdot}79\, C_D\frac{S}{C}-1{\cdot}12\left(C_D\frac{S}{C}\right)^2\right] \quad (3)$$

Over a wider range of values of $C_D\frac{S}{C}$ there would almost certainly be additional terms in higher powers of $C_D\frac{S}{C}$, otherwise these expressions would lead to a diminution in the value of C_D when S/C exceeds about 0·4, which is clearly not true.

The slight reduction in the drag coefficient of the plates near the roof as compared with centrally mounted plates must be in part associated with the effect of the boundary layer at the walls, which was about 2 in. (5 cm) thick at the balance position.

The interesting conclusions from the preliminary tests are that:

(a) Position of the model in the tunnel has no significant effect on the wake blockage correction.

(b) Measurements made to determine blockage corrections with large models subject to separated flow (i.e. where a large effect is available for measurement) can be used by linear interpolation to deduce with sufficient accuracy the blockage corrections on smaller geometrically similar models, since the departure of the curves of Figs. 2 and 3 from linearity are small.

3. *Main Programme of Tests.*

3.1. *Introduction.*

Maskell's paper[1] is based on his colleague's tests[2] on centrally-mounted thin flat plates used singly in a closed wind tunnel. This was almost certainly the first paper giving information on such plates fully corrected for blockage effects. The connection between aspect ratio, drag coefficient and blockage correction is clearly established in these papers.

However, in non-aeronautical testing, much of the interest is centred on wall-mounted models representing structures in a natural wind. Early work by Irminger and Nokkentved[3] suggested that the drag coefficients of wall-mounted plates were almost constant from $h/b = 1$ to $h/b \rightarrow 0$ at a value around 1·2. This is markedly in contrast with the corresponding values from 1·15 to 1·86 for centrally mounted plates, which could be regarded as equivalent to wall mounted plates of half the height when considered with their images in the wall. This raised doubts that blockage factors on wall-mounted plates should be the same as those on centrally-mounted plates, even when the aspect ratio of the floor-mounted plate is based on $2h/b$ to include the image.

A further topic of interest was the problem of blockage corrections on one structural model when another model was in the tunnel (not necessarily in the same plane) to simulate a full scale site grouping arrangement. Fundamental to such a problem was the question as to whether the 'active' blockage effect experienced by a model due to its own presence in a wind tunnel was the same as the 'passive' blockage effect experienced by another model even of infinitesmal area, in the same plane, and how this depended on the size of the models.

These subjects were studied by assuming that the total blockage effect in a transverse plane was dependent on the total drag in that plane per unit area, that active and passive blockage effects were the same between identical models in the same plane so that the effect could be considered separately and superposed. From such considerations it was possible to derive an expression for the ratio of the drag of one plate in the presence of another to the drag of this plate alone in the tunnel. For the particular case when both plates were in the same plane, the blockage factor of one plate, as derived from the change in drag of the other, should have been the same as the blockage factor of the same plate, as derived from the previous single-plate measurements in the preliminary programme. If this was found to be true then, it was argued, the initial assumptions were valid and the method could be used to investigate the blockage factors when the plates were not coplanar. The theoretical basis of the method is described in Appendix B.

3.2. *The Measurements.*

A plywood plate 26 in. wide and 13 in. high (66 × 33 cm) chamfered around the perimeter at the rear, was mounted on the balance within 1/8 in. (3mm) of the roof, normal to the wind direction. This plate was used to measure the blockage factor of an identical plate normal to the floor, over a range of distances upstream and downstream of the upper plate. The method is described in detail in Appendix C.

The upper plate, thus calibrated, was then used to determine the corresponding blockage factors of other plates of varying sizes and height/breadth ratios. Then an open grid structure (open area ratio 0·46) was used instead of the lower plate and its blockage factor measured over the same range of positions. The open grid structure was augmented by an identical structure with connecting bars to form an open box structure (Fig. 5) and this was tested in the same way.

3.3. *Discussion of Results.*

As described in Appendix C one of the stages in the measurement of the blockage factor of a plate is the measurement of its drag in the tunnel. After the measurement of the blockage factor it is possible to correct the drag coefficient to a free-air value. The upper graph in Fig. 6 shows how the corrected drag coefficients of a series of wall-mounted plates varied with their height to breadth ratio. The dotted line compares the drag coefficients of centrally-mounted plates* having the proportions of the floor-mounted plate and its image in the floor. This shows that the drag coefficients of taller ground-mounted plates are comparable with centrally-mounted plates but as Irminger and Nokkentved[3] suggested the drag coefficients of very broad floor-mounted plates might well tend to a constant value.

The lower graph in Fig. 6 shows the values of n_0, the blockage factor in the plane of the plate, for wall mounted plates of differing aspect ratios. The values plotted as circles were evaluated from balance measurements by linear expressions derived in Appendix B. However the areas of the plates tested varied over a range of nearly 5:1 so that some points would be affected more than others by the non-linear effects experienced by large plates. Since the values of n_0 calculated in this way varied so little over the range of aspect ratios from 1/3 to 3, it seemed reasonable to expect the magnitude of the non-linearity terms also to vary little with aspect ratio. The measured values of n_0 were modified by adding varying amounts corresponding the term $1{\cdot}12\, C_D\, S/C$ which expressed the non-linearity for $b = 2h$ plates (*see* Fig. 3). The modified values of n_0 were then considered as representing small-model conditions for the various aspect ratios represented.

The corrected values are compared with the blockage factors of centrally mounted plates representing the wall-mounted plate and its image, where the blockage factor n_0 is taken as $-1/C_{p_{bc}}$. It would seem that small wall-mounted plates with aspect ratios from 1/3 to 3 have identical values of n_0 within the accuracy of these experiments.

Of particular interest was the encouraging agreement between the values of n_0, for three plates of differing size but each with $b = 2h$, deduced in one case from the changes in drag of an upper plate on the balance, in the other from the measured drag coefficients of the plates alone.

The former values, corrected to small-plate conditions averaged 2·84 (as seen in Fig. 6) whereas the latter were related to the small-plate value 2·79 (Fig. 3). This agreement was felt to indicate that the assumptions underlying the theoretical basis of the method were sound.

The measurements of blockage factor for a series of wall-mounted plates over a range of distances upstream and downstream of the plate were initially difficult to understand. When plotted on the basis of actual axial distance x from the plate there seemed a remarkable similarity between blockage factors for different plates for distances upstream of the plates, but wide disparity between values downstream of the plates. This seemed surprising if the upstream effects were to depend on plate size, since the mean side ($\sqrt{S}$) of the plates involved varied between 13 in. and 22·5 in. (33 and 57·1 cm), and yet the upstream results seemed to be independent of the plate size. After trial methods of plotting, it was found that the upstream effects varied according to x and the downstream effects according to $x/\sqrt{S}$. This suggested that the upstream non-dimensional parameter was probably $x/\sqrt{C}$.

To confirm this some further tests were made in the NPL 13 ft × 9 ft tunnel, where $\sqrt{C}$ was 122·8 in. (3·12 m) instead of 80·5 in. (2·05 m) as in the 7 ft × 7 ft tunnel. The tests were over a limited range of distances (because of the short working section) and on two plate sizes only.

The results of the combined measurements are shown in Figs. 7 and 8.

To eliminate the complication of the slight non-linearity already found in values of n_0 (and presumably similarly present in values of n) values of the attenuation factor n/n_0 were used for plotting. It should be

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*The data for centrally-mounted plates were derived from tabulated results by Fail, Lawford and Eyre[2]. The present author has found that these tabulated results can be summarised by the expressions:

$$C_{D_c} = 1{\cdot}103 + 0{\cdot}0198\,(h/b + b/h) \quad (4)$$

and

$$-C_{p_{bc}} = 0{\cdot}333 + 0{\cdot}01735\,(h/b + b/h) \quad (5)$$

for $1/40 \leqslant h/b \leqslant 40$

noted that Fig. 7 includes results for wall-mounted models ranging from plates with $3 \geqslant h/b \geqslant 1/3$, to the single grid and double grid models. By logarithmic plotting it was found that the points were best represented by a curve of the form

$$n_{-x}/n_0 = e^{-(\pi^2 x^2/4C)}$$

The only theoretical work known on the upstream effects of blockage is that by Allen and Vincenti[4] which relates to two-dimensional models. The attenuation factor found by these authors takes the form

$$n_{-x}/n_0 = 1-\coth(\pi x/\sqrt{C})+(\sqrt{C}/\pi x) \tag{7}$$

in this case $\sqrt{C}$ is the height of the two-dimensional tunnel. Values of n_{-x}/n_0 calculated from equation (7) decayed much more slowly with upstream distance ($-x$) than the present experimental results and have not been plotted in Fig. 7. Perhaps theoretical work in the future will show the link between the parameters $(\pi x/2\sqrt{C})$ and $(\pi x/\sqrt{C})$ in the two expressions. One obvious connection would seem to be in a theoretical system in which the floor-mounted model and floor were treated as a centreline model of twice the height, in a tunnel of twice the height. For present purposes, however, an empirical solution would seem sufficient.

Within the accuracy of the experiment there seemed sufficient distinction between results for the values of blockage factor downstream of differing aspect ratio plates to merit separate curves as shown in Fig. 8. The relatively rapid attenuation for such plates in the downstream direction must be connected with the mixing effect due to the strong turbulence of large scale in the wake of the plates.

In Fig. 9 it will be seen that no such attenuation was present behind the open grid models, where the turbulence scale was obviously much smaller and related to the mesh size and the width of the bars. In this figure the origin for plotting the blockage factors for the double grid model was an effective position, at distances from each grid plane inversely in proportion to the drags of the two constituent plane grids when in the assembled position. These separate drags were deduced from differences between the drags of a single grid and the complete model. The effective centre was about one-third of the overall depth of the model from the front face.

The downstream section of this graph could not be plotted on Fig. 8 for want of an area parameter $\sqrt{S}$ appropriate to the wake dimensions. The upstream section fitted Fig. 7 exactly with the essential difference that n_0 was only 1·28.

It is interesting to consider the grid models as bars mounted in the free stream (as distinct from the wall-mounted plates considered so far). C_{D_c} for the single grid, based on the frontal area, was measured as 1·69. From equation (4) it is known that this drag coefficient applies to thin rectangular plates of aspect ratio 29·6. Alternatively, since $n_0 = -1/C_{p_{bc}}$ for thin plates, a blockage factor of 1·28 corresponds to a base pressure coefficient of 0·78, which from equation (5) applies to a plate of aspect ratio 25·8. Thus on the evidence of both drag coefficient and blockage factor the open lattice grid behaves like a thin flat plate of aspect ratio rather less than the infinite value usually assumed.

It is interesting to note that the blockage factor for the complete grid model is almost unchanged even though some of the drag on which it is calculated has been seriously affected by shielding from the upstream element.

It has been emphasized that the distinction between the open lattice model and the solid plates was that the open area ratio was sufficiently high (0·46) for the lattice model to be considered as individual long bars. For a lattice model with a much higher open area ratio it is possible that the flow associated with the individual bars could become more nearly two-dimensional, so that the value of n_0 would lie somewhere between the measured 1·28 and a theoretical, but improbable, 0·94 for the two-dimensional case ($C_{p_{bc}} = -1·08$). Undoubtedly also, as the open area ratio decreases towards zero n_0 will rise towards 2·79. For all open area ratios the upstream behaviour will be in accordance with Fig. 7. The downstream behaviour will be intermediate between that represented by Fig. 9 and Fig. 8 if the open area ratio is less than 0·46, being governed both by the open area ratio and the size of the mesh.

Thus it would seem reasonable to use a blockage factor n_0 of about 1·28 for any open lattice model with an open area ratio of about 0·4 or more consisting of thin elements, calculating the blockage correction on the measured drag of the whole model. This offers a more attractive method than the use of a separate blockage factor for the shielded elements coupled with velocities reduced in a ratio of other empirical shielding factors, as seemed likely before these tests were made.

4. *Conclusions.*

Following this investigation, the author concludes that:

(1) Maskell's wake blockage corrections for a model subject to separated flow apply regardless of the position of the model relative to the tunnel axis.

(2) These corrections need only minor modification for non-linearity even when the correction on drag approaches 100 per cent.

(3) The wake blockage effect experienced by a second model due to the presence of a co-planar model in a tunnel of closed section is the same as that experienced by the first model and *vice versa.*

(4) It is possible to superpose the active and passive wake blockage effects due to two or more models in the tunnel at the same time, provided each model is well clear of the wake of the others. On this basis equations have been derived for the overall wake blockage effects on two models in the tunnel at the same time. (Appendix B). A method of determining the relevant blockage factors for this purpose is also described (Appendix C).

(5) Wall-mounted rectangular plates with $h > b$ tend to behave for drag purposes as centrally-mounted plates with sides in the ratio $2h:b$, provided the wall boundary layer is thin.

(6) Small wall-mounted rectangular plates where $h < 3b$ (and possibly for higher values of h/b not tested) all have the same wake-blockage factors provided the wall boundary layer is thin. Larger plates have slightly reduced blockage factors. In the NPL 7 ft × 7 ft wind tunnel the value of the wake blockage factor n_0 for $b/h = 2$ wall-mounted rectangular plates was found to be $n_0 = 2{\cdot}79 - 1{\cdot}12\,(C_D\,S/C)$.

(7) The wake blockage factor for wall-mounted models in any plane decreases with distance ahead of the model. The attenuation factor applying to rectangular plates and lattice models was found to fit the empirical expression

$$n_{-x}/n_0 = e^{-(\pi^2 x^2/4C)}$$

The attenuation factor at planes downstream of the models is probably related to the size of their wakes and is close to unity for a considerable distance behind open lattice models. Experimental values of this factor for some wall-mounted plates and lattice models are shown in Figs. 8, 9.

LIST OF SYMBOLS

b	Width of plate
C	Cross-sectional area of working section
C_D	Drag coefficient D/qS
C_p	Pressure coefficient $(p-P)/q$
C_{p_b}	Separation-pressure coefficient $(p_b-P)/q$
D	Drag of plate A alone in tunnel for dynamic pressure q
D'	Drag of plate A in presence of plate B for dynamic pressure q
h	Height of plate
m	Blockage factor in general: blockage factor for plate A — Equation 1
n	Blockage factor in general: blockage factor for plate B — Equation 1
p	Surface pressure at any position on model
p_b	Surface pressure at separation point. Base-pressure for thin plate normal to stream
P	Static pressure in undisturbed stream
q	Dynamic pressure of undisturbed stream
R	Drag of plate B alone in tunnel for dynamic pressure q
R'	Drag of plate B in presence of plate A for dynamic pressure q
S	Area of model chosen to define drag coefficient
x	Distance from plane of model, positive downstream
z	Distance from floor or roof
Suffix c	Corrected for blockage
Suffix o	In own plane ($x = o$)
Suffix $(+x)$	At distance x downstream of own plane
Suffix $(-x)$	At distance x upstream of own plane
Suffix ∞	Value which would have obtained in the absence of tunnel walls

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APPENDIX A

The Separation of Genuine Wake Blockage Effects from Speed Measurement Errors.

The presence of a large model in a wind tunnel will produce genuine wake-blockage effects. It may in addition affect the static pressure in the region of wall-pressure tappings used to measure wind speed (e.g. in a contraction ahead of the working section). Thus unless steps are taken to eliminate errors in the measurement of tunnel speed, genuine wake blockage effects cannot be studied separately.

For models in the balance plane of the NPL 7 ft $\times$ 7 ft tunnel the approach dynamic head had previously been measured in terms of the pressure difference between sets of static holes at each end of the 7·15:1 contraction. For the present tests three further static holes were fitted on the contraction wall fillet at positions where the sectional area was about 12, 18 and 28 per cent above that at the end of the contraction. The pressure difference between each of the new holes and the upstream set of holes was measured both in the empty tunnel and with a floor-mounted 20 in. $\times$ 40 in. (50·8 $\times$ 101·6 cm) plate normal to the tunnel axis at 2 ft (61 cm) downstream of the end of the contraction, representing the extreme limits of any possible interference effects. The ratios of each of the pressure differences with the board in place to the corresponding pressure differences with the tunnel empty were evaluated. Even for the combination using the nearest of the new holes the ratio was found to be within 0·5 per cent of unity. On the evidence of these measurements the downstream hole was selected for use with the holes upstream of the contraction to monitor the approach dynamic head in all the subsequent experiments on blockage. In this way it was ensured that errors in measuring the approach dynamic head were not mistaken for genuine blockage effects.

APPENDIX B

Wake Blockage Interference Between Two Models.

(a) *Plate-type models.*

Let us consider a wind tunnel with a closed section of area C, having thin boundary layers and one balance, for the sake of argument a roof-balance as in the 7 ft × 7 ft tunnel. Let the tunnel be run at a constant approach dynamic head q (far ahead of the models).

Let us suppose there are two flat plates always mounted normal to the wind whose free-stream drags for a dynamic head q are D_∞, R_∞. If these are placed separately on the balance the drag recorded will be D and R, due to their respective blockage factors m_0 and n_0 (where the suffix o denotes in its own plane i.e., $x = 0$ from the plate).†

If the first plate is fixed to the roof balance and the second mounted normal to the floor at a distance x upstream, the drag of the roof-mounted plate will increase to D' due to its own blockage factor m_0 and to the blockage factor of the other plate $n_{(+x)}$, the latter representing the blockage effect of the second plate at a distance x downstream of its own plane (*see* Fig. 4). Similarly the drag of the floor-mounted plate will increase to R' due to its own blockage factor n_0 and to the blockage factor of the roof-mounted plate, $m_{(-x)}$ at a distance x upstream of its own plane.

We may calculate these effects from Maskell's expressions as long as we assume the principle of superposition to hold for plates each outside the wake of the other.

For a single plate in the tunnel:

$$D = D_\infty (1 + m_0 D/qC) \tag{8}$$

$$R = R_\infty (1 + n_0 R/qC). \tag{9}$$

With two plates in the tunnel:

$$D' = D_\infty (1 + m_0 D'/qC + n_{(+x)} R'/qC) \tag{10}$$

$$R' = R_\infty (1 + n_0 R'/qC + m_{(-x)} D'/qC). \tag{11}$$

Re-arranging (8),

$$D (1 - m_0 D_\infty/qC) = D_\infty \tag{12}$$

and from (10)

$$D' (1 - m_0 D_\infty/qC) = D_\infty (1 + n_{(+x)} R'/qC). \tag{13}$$

Dividing (13) by (12)

$$D'/D = 1 + n_{(+x)} R'/qC. \tag{14}$$

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†It is conventional to consider blockage effects in terms of a rise in upstream dynamic pressure from q and q_c. In the present treatment the author has found it more convenient to consider q unchanged and the drag increased from D_∞ to D by the presence of the tunnel walls. The two systems are linked by the expressions $C_{Dc} = \dfrac{D}{q_c S} = \dfrac{D_\infty}{qS}$.

Similarly,

$$R'/R = 1+m_{(-x)}\,D'/qC\,. \tag{15}$$

Hence

$$D'/D = 1+n_{(+x)}\,(R+m_{(-x)}\,RD'/qC)/qC\,. \tag{16}$$

This may be re-arranged to give

$$\frac{D'}{D} = \frac{1+n_{(+x)}\,R/qC}{1-n_{(+x)}\,m_{(-x)}\,RD/q^2C^2}\,. \tag{17}$$

In an alternative form

$$n_{(+x)}\,R/qC = \frac{(D'/D)-1}{1+(D'/D)\,m_{(-x)}\,(D/qC)} \tag{18a}$$

or when the lower plate is downstream of the upper plate,

$$n_{(-x)}\,R/qC = \frac{(D'/D)-1}{1+(D'/D)\,m_{(+x)}\,(D/qC)}. \tag{18b}$$

These relate the increase in drag of the balance-mounted plate, when the second plate is introduced, to the measured drags of the plates placed in turn in the tunnel, and to the blockage factors of the two plates as each affects the other. This equation is most useful for determining the variation of the blockage factor of a model over a range of distances upstream and downstream.

For the correction of wind-tunnel measurements a more convenient form is

$$\frac{D_\infty}{D'} = \frac{1-n_{(+x)}\,m_0\,RD/q^2C^2}{(1+n_{(+x)}\,R/qC)\,(1+m_0\,D/qC)} \tag{19}$$

(b) *Block-type models.*

The above treatment for pairs of flat plates normal to the wind is only possible because the separation drag (responsible for wake-blockage effects) is equal to the total drag of such models measured with a balance.

For a model of rectangular-block form, arbitrarily inclined to the wind, the drag measured on a balance consists of the separation drag modified by drag components dependent on the lateral force and on the pressure field within the wake enclosing the model.

One can determine the separation drag coefficient approximately for such a model from a graph of the measured drag coefficient *versus* the square of the lateral-force coefficient over a range of inclinations to the wind. Such a procedure is mentioned by Maskell[1] in connection with lifting aircraft models.

However, Cowdrey[5] has shown that the blockage effect of a single rectangular-block model, which is neither sufficiently deep (in the wind direction) nor sufficiently inclined to the wind to cause re-attachment of the separated wake on the model, is identical to that for the plat plate corresponding to the forward face of the model bounded by the separation line.

This fact enables the blockage correction on one such model in the presence of another to be calculated with reasonable accuracy.

Consider the two flat plate models equivalent to such a pair of models.

For the first, equation (18a) gives

$$(D'/D)_1 = \frac{1+n_{(+x)}\,R/qC}{1-n_{(+x)}\,n_{(-x)}\,R^2/q^2C^2} \tag{21}$$

and for the second reading, equation (18b) gives

$$(D'/D)_2 = \frac{1+n_{(-x)}\,R/qC}{1-n_{(+x)}\,n_{(-x)}\,R^2/q^2C^2} \tag{22}$$

leading to the useful result,

$$\frac{D'_1}{D'_2} = \frac{1+n_{(+x)}\,R/qC}{1+n_{(-x)}\,R/qC}. \tag{23}$$

Initially by assuming that $n_{(-x)} \rightarrow 0$, an approximate value of $n_{(+x)}$ was obtained. Then substitution of this value into equation (22) a better value of $n_{(-x)}$ was obtained. This process was repeated, using each of equations (21), (22) and (23) in turn to give values of $n_{(+x)}$ and $n_{(-x)}$ which satisfied all three equations.

This procedure was repeated when the lower plate was moved into other pairs of positions each closer to the plane of the upper plate. As the process continued the provisional graph of results made it possible to make better estimates of the approximate values of $n_{(-x)}$ and thus to shorten the iterative process.

In this way a complete series of blockage factors was obtained for the identical pair of plates chosen. One of these plates was used on the balance in all subsequent tests with a variety of other plates and models on the floor. From this stage onwards it was possible to cover the range of positive and negative values of x in single positions, and since $m_{(+x)}$, $m_{(-x)}$, and D/qC were all known for the calibrated plate equation (21) or (22), as appropriate, enabled values of $n_{(+x)}$, $n_{(-x)}$ to be estbalished for each of the other models.

It is worth emphasising at this stage that there is an implicit assumption that the area of tunnel containing the upper plate has the same approach velocity in the empty tunnel as that containing the lower plate.* However, small discrepancies between roof and floor distributions can be nullified by the modification of the value of the term D/qC, associated with the drag of the upper plate in equations (18a, 18b), in the ratio of the mean dynamic head at the upper plate to that at the lower plate. For this purpose the mean dynamic head may be taken as $\frac{1}{h}\int_0^h u^2\,dz$, where h is the height of a plate, and the integration covers the position of each plate with the tunnel empty. This method has been found to give identical values of drag coefficients for floor mounted plates in a uniform stream and in a deliberately induced thick boundary layer deeper than the model. Since the air flows over sharp-edged bluff models are not very sensitive to scale effects, precise wind speed setting is unnecessary so that time can be saved if values of D/qC and such terms are obtained from simultaneous readings of drag and dynamic head whenever steady conditions exist.

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*A common, but not always detected source of maldistribution of velocity in a wind tunnel is the uneven choking of screens by dust, etc.

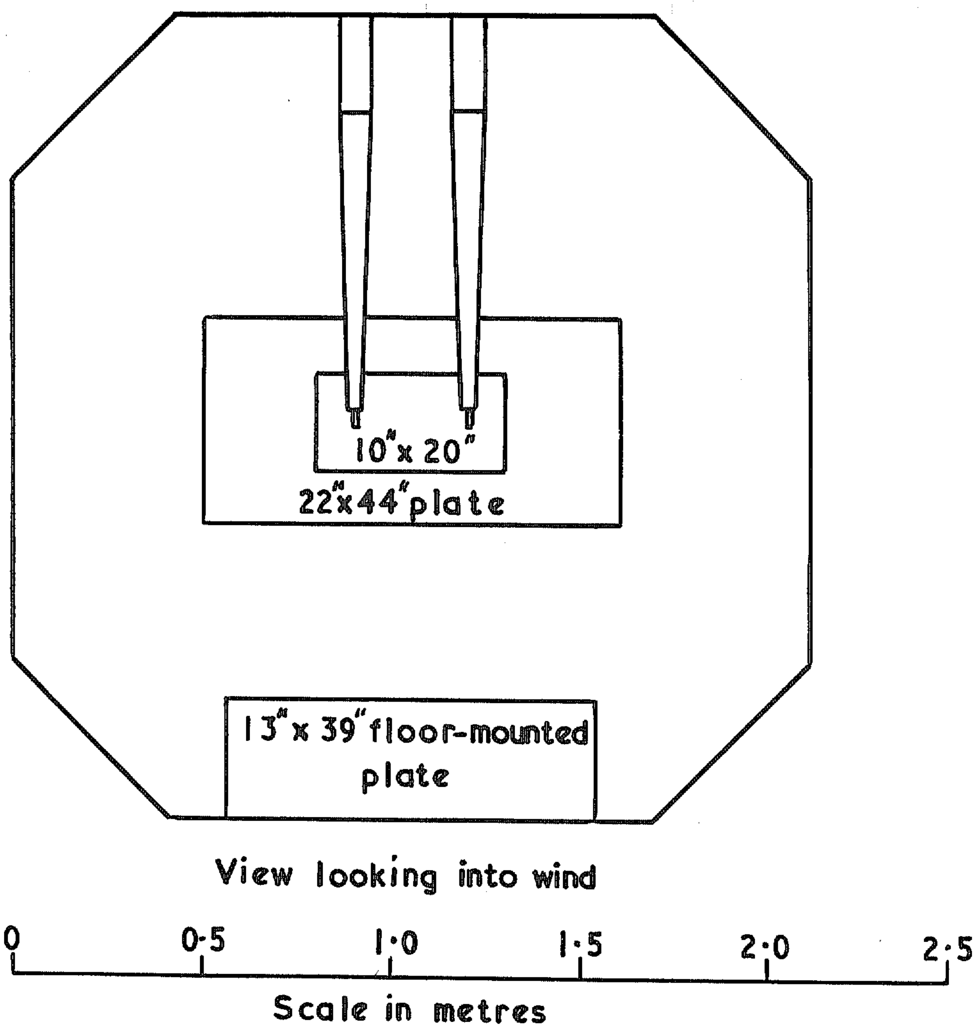

FIG. 1. Section of 7′ × 7′ wind tunnel showing position of balance guards and clearance between fillets and broadest floor-mounted plate.

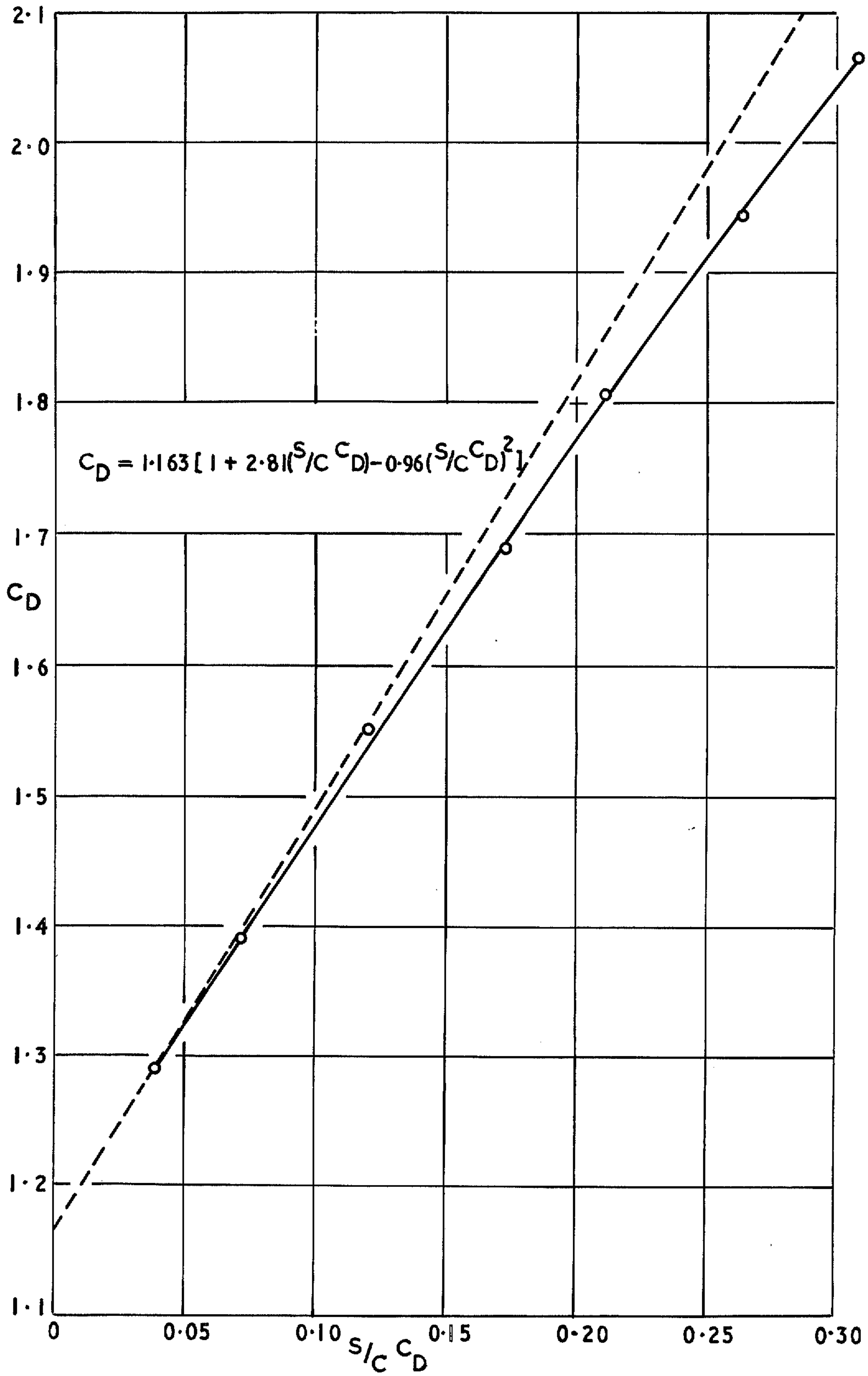

FIG. 2. Drag measurement on $b = 2h$ flat plates normal to wind on tunnel axis.

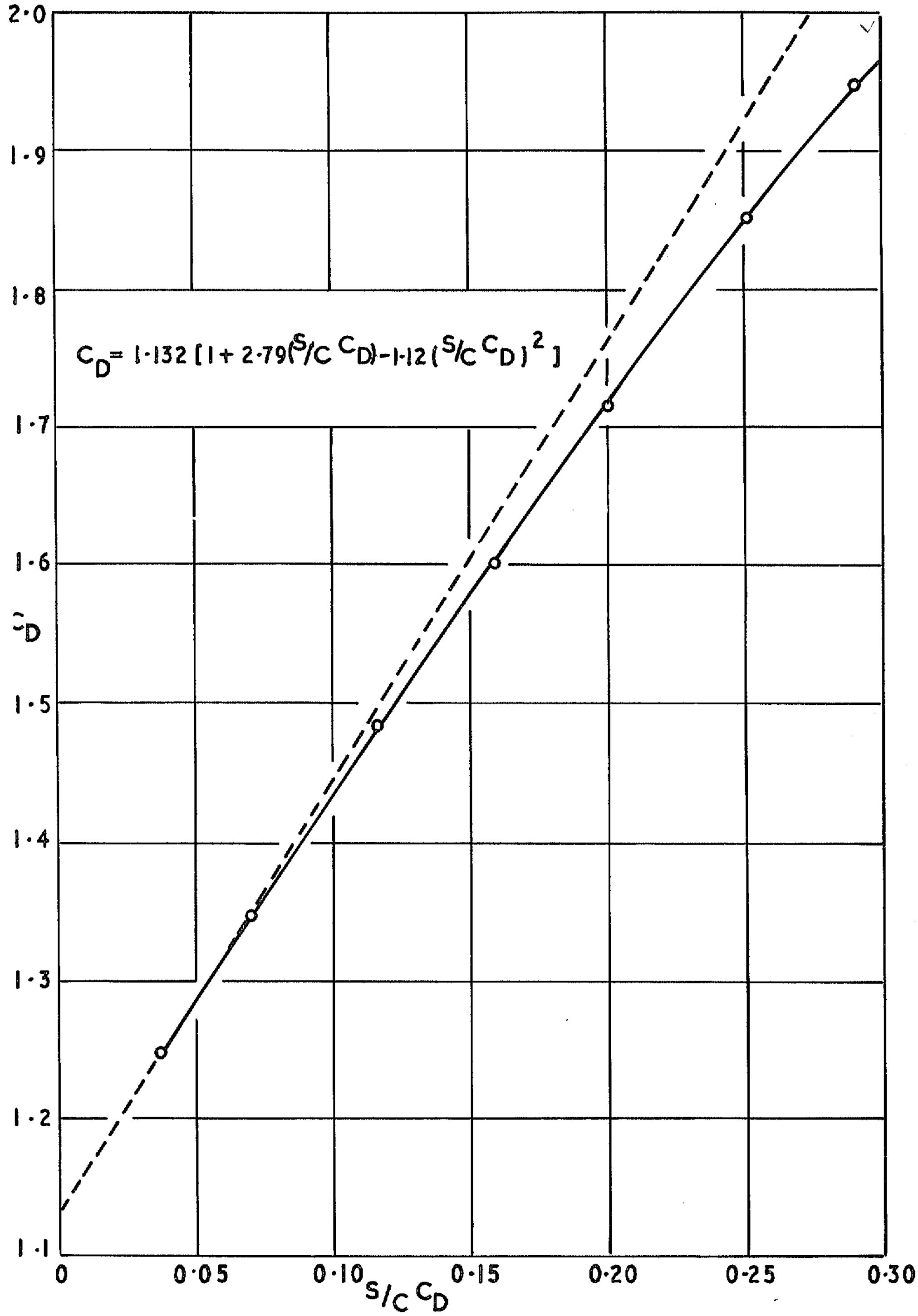

FIG. 3. Drag measurements on $b = 2h$ flat plates normal to wind adjacent to roof of tunnel.

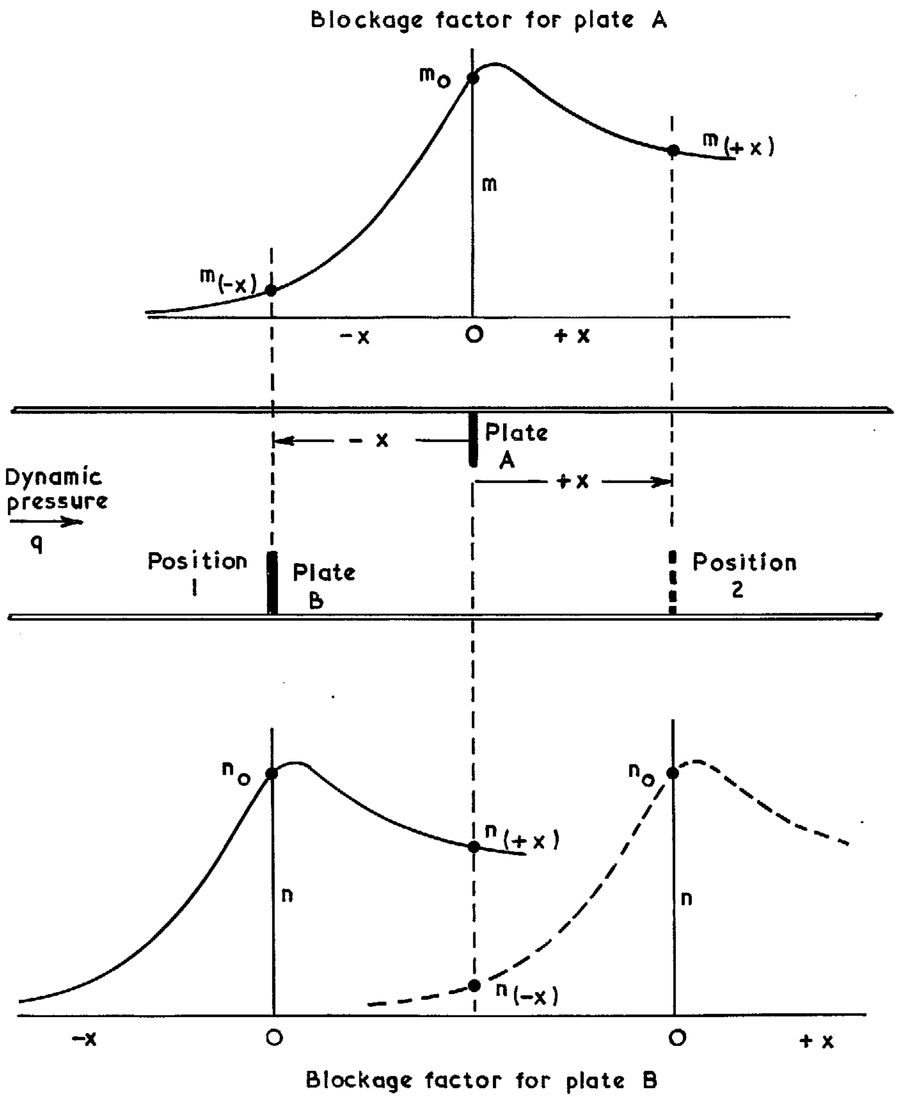

FIG. 4. Notation for mutual blockage effects between two plate models in a closed-section wind tunnel.

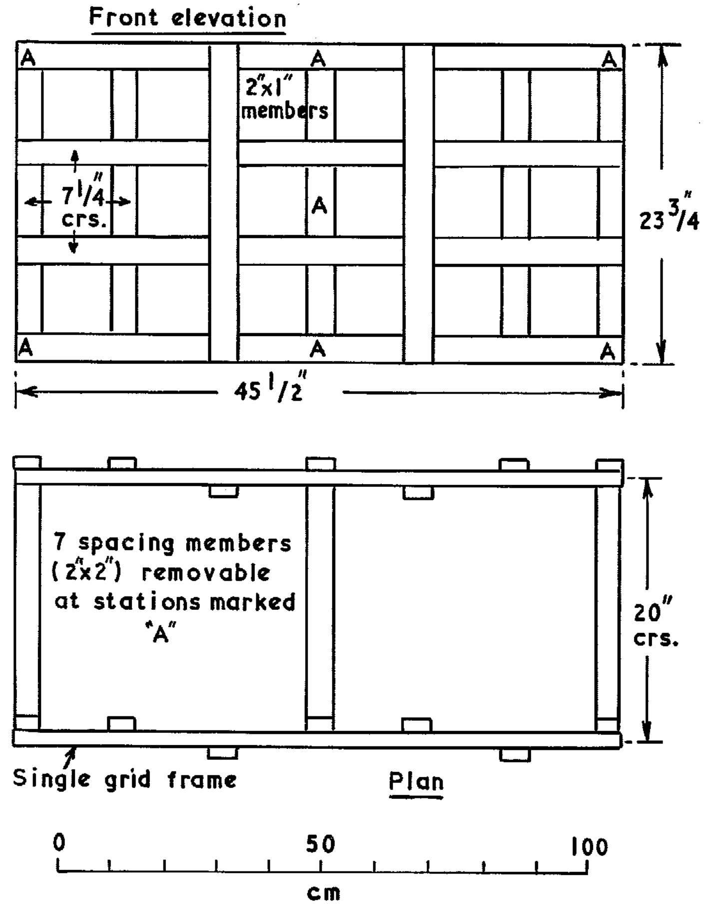

FIG. 5. Construction of single and double grid models.

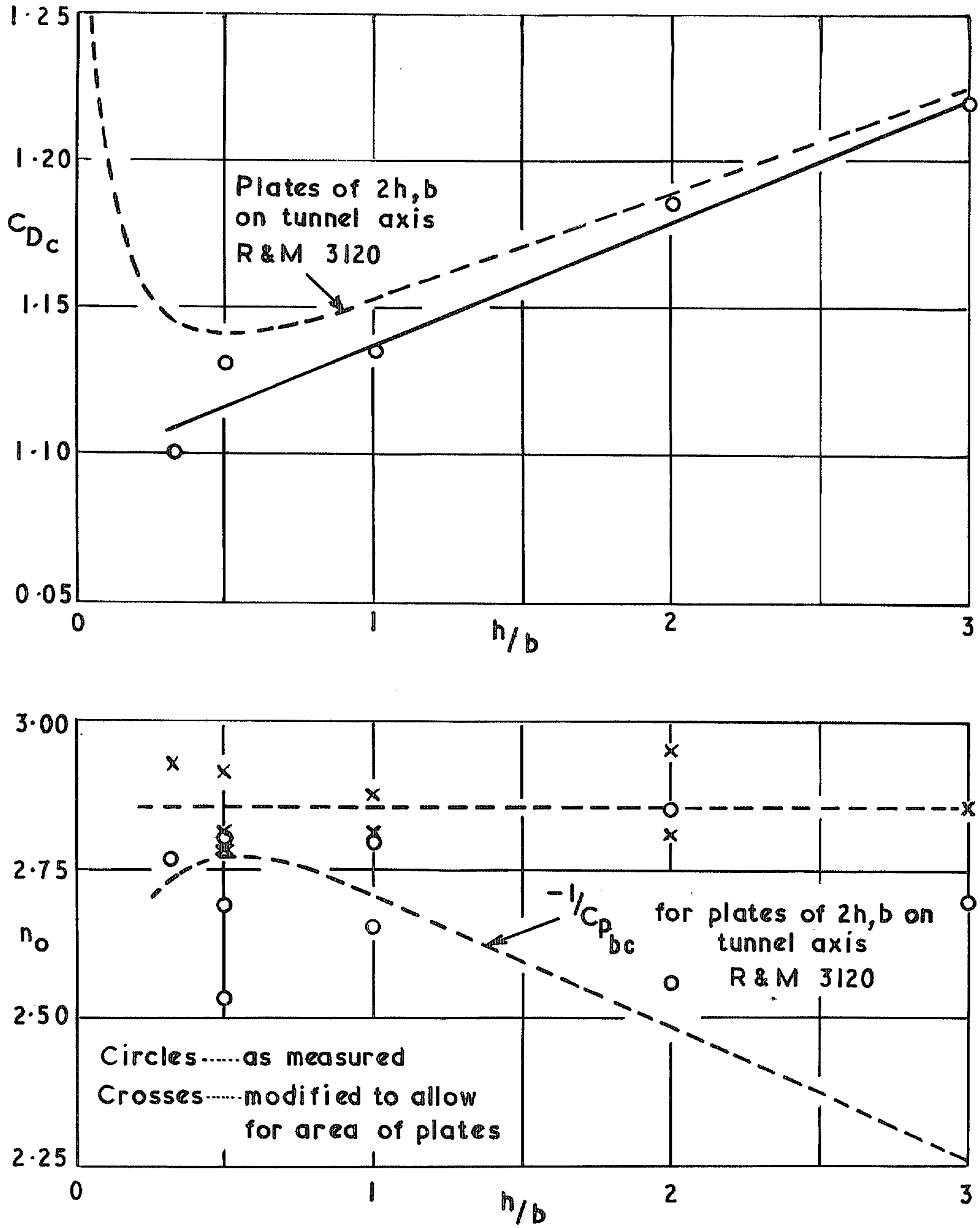

FIG. 6. Values of corrected drag coefficients and blockage factors for wall-mounted plates of various aspect ratios.

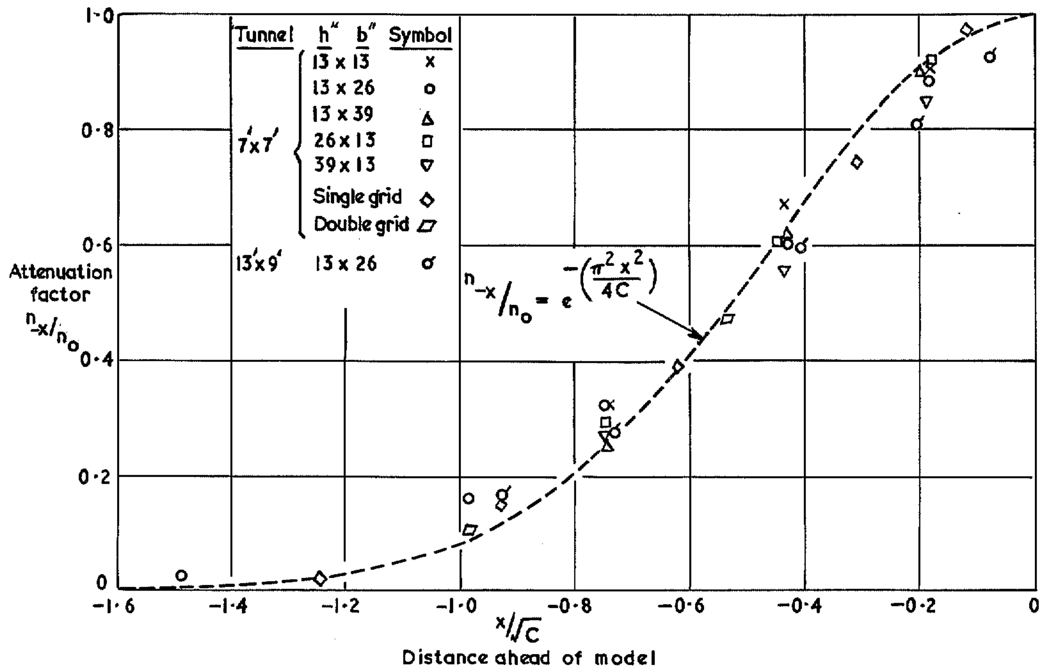

FIG. 7. Upstream interference due to wall-mounted models normal to wind.

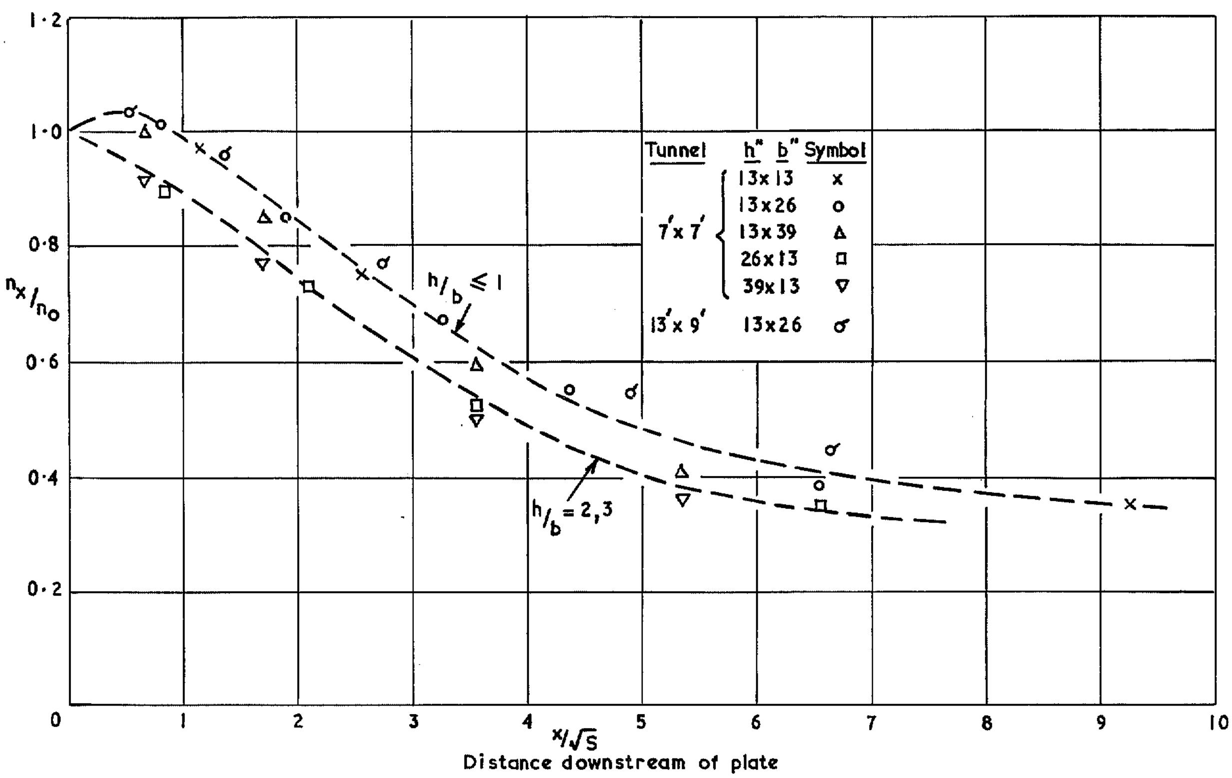

FIG. 8. Downstream interference due to wall-mounted plate models normal to wind.

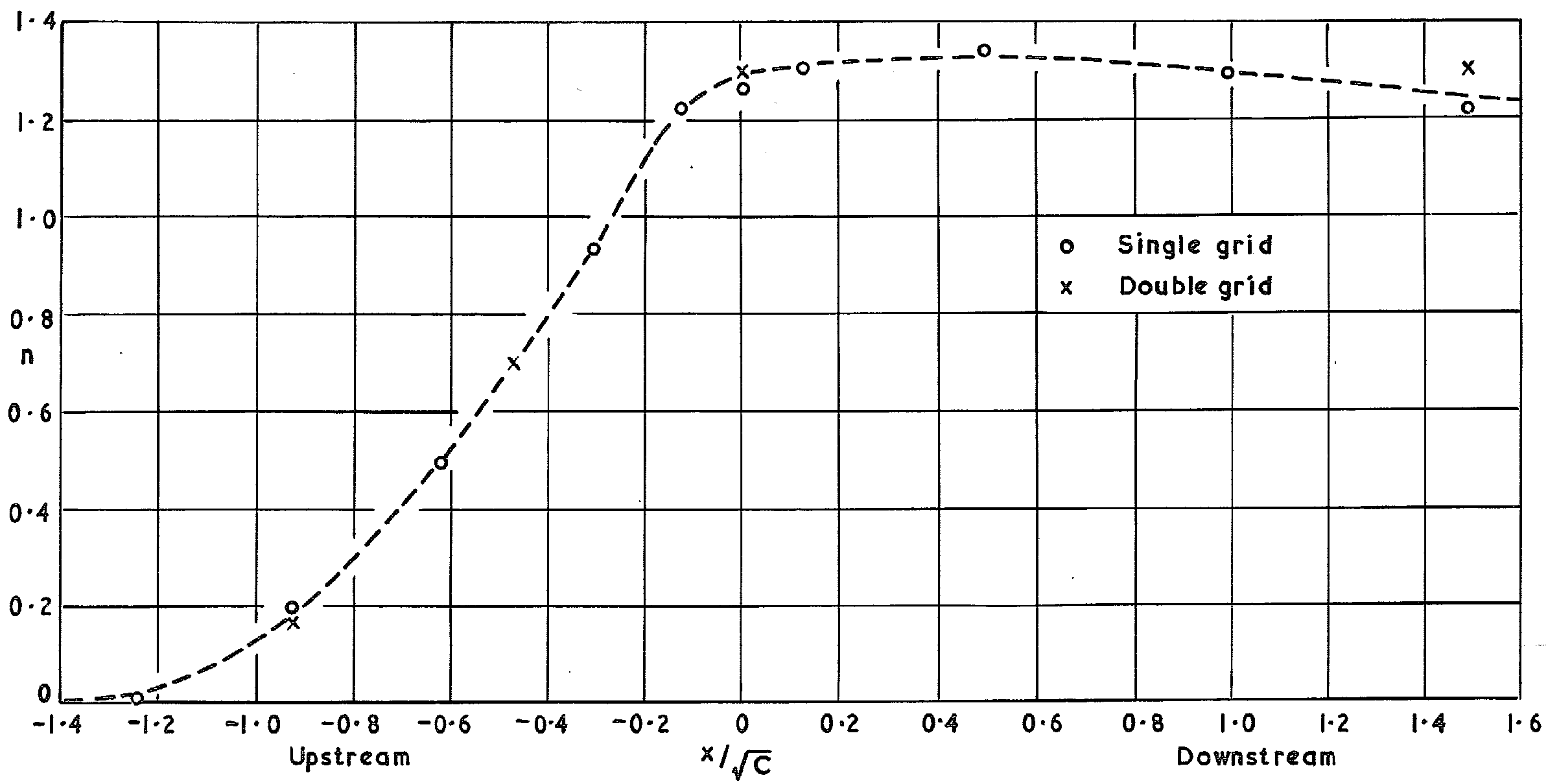

FIG. 9. Interference due to floor-mounted grid models.

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