EFFECTS OF VELOCITY DISTRIBUTION ON WIND LOADS AND FLOW PATTERNS ON BUILDINGS

by

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SUMMARY

PRESSURE distributions on models of walls and rectangular-block structures have been measured in a wind tunnel. The tests were conducted both in an artificially produced velocity gradient, used to simulate natural conditions, and in a constant velocity field, for comparison with standard procedures. Several rules have been deduced from the results by which pressure distributions and wind loads can be predicted for buildings in any specified wind field. Changes in the flow pattern due to the velocity distribution have been observed and correlated with the pressure distribution. Only on the front surfaces were distinct phenomena observed: an intense downward flow carrying high energy air to ground level exists on tall buildings, and on low structures a region of reversed flow occurs at ground level resulting in an attached eddy.

1. INTRODUCTION

In many instances of contemporary design practice, wind loads are assumed to be the result of a steady wind with constant velocity at all elevations above ground level. Under these assumptions the pressure p at any point on the structure can be related to the ambient pressure p_o and the constant velocity V_o through the pressure coefficient

$$c_p = \frac{p - p_o}{\rho V_o^2/2}$$ where ρ is the ambient density of the air.

If the structure has sharp corners and wind velocities are of the order of 5 mi./hr. or more, the theory of flow around bluff bodies indicates that c_p is a unique function of the wind direction relative to the building. For a few simple shapes the values of c_p can be deduced from certain classical experiments in aerodynamics. However, for the large majority of practical cases, wind-tunnel tests are required for each indiviual structure shape and orientation with respect to the wind direction. Thus there results a catalogue of pressure coefficients for every building geometry. While there is no all-inclusive listing of these coefficients, a very large number of building shapes have, for instance, been tested at the Iowa Institute of Hydraulic Research, and the results correlated and summarized(1). Furthermore, average values for building surfaces have also been assembled from various sources and issued in handbook form for design purposes(2). However, it is widely recognized that any extraordinary shape must still be studied in scale model tests in a wind tunnel.

The commonly adopted testing procedure neglects two major meteorological characteristics, i.e. the gustiness of the wind and the variation of velocity with height. These phenomena are not independent but are the natural consequence of the friction of the earth's surface on the motion of large air masses. It can easily be deduced that the rougher the surface the more gusty (unsteady) the wind and the greater the curvature in the velocity distribution.

Turbulence of the natural wind field has been measured in the field and found to have the same general properties as wind-tunnel turbulence. However, there is a very large difference in the size of the eddies. In a conventional wind tunnel the eddies are an order of magnitude or more smaller than the size of the model, whereas in the field the eddies are an order of magnitude larger than the structure. The effect of these large eddies on wind loads has been discussed by Davenport(3) who has shown that the dynamic properties of the building influence the resulting wind loads. A few simple cases have been analyzed but much remains to be done. It is evident from Davenport's work that conventional wind-tunnel tests do not give an indication of the size of these dynamic loads.

The natural velocity distribution can, however, be readily reproduced in a wind tunnel and the loads resulting from this effect analyzed. Screens and grids can be installed in the tunnel test section and any velocity distribution produced. Pressure distributions can be readily measured and local values of the pressure coefficient c_p obtained. The reference velocity V_o used here is that of the undisturbed wind field at the elevation of the top of the building. The inclusion of still another variable (i.e., the velocity distribution) on which the pressure coefficients are dependent further complicates the presentation of test results. A given plot will now show results for only one shape, one orientation and one distribution so that many tests of a particular building would be required to give a complete picture. There are, however, trends observed in tests on simple shapes which can be of real help to designers in estimating the loads on buildings of more complex shape.

This paper presents the most significant results of a programme of measurements of pressure distribution on typical building shapes in a low-speed wind tunnel. Two wind fields were used. One of constant velocity represented typical standard wind-tunnel test conditions; for the other a velocity distribution approximating that in the atmospheric boundary layer was developed. The distribution selected was typical of urban conditions as defined by Davenport(3). The models in every case had sharp corners and rectangular plan section to minimize scale effects. Attempts were also made to apply the principles of flow around bluff bodies to give analytical procedures for the prediction of pressure distribution for any velocity field. However, this approach was successful only for tall buildings. For low buildings, i.e., with heights roughly equal to the lateral dimensions or less, the pressure distribution cannot be predicted, but total loads can be predicted to the accuracy common in practice.

2. PRESSURE DISTRIBUTION AROUND BUILDING SHAPES

Virtually all building shapes are classified as bluff bodies and thus have distinctly different pressure distributions from streamlined bodies such as air foils and submarine hulls. The distinguishing property is the wake of separated flow surrounding the rear part of the body. As sketched on *fig.1* the flow approaching the body is deflected by the front facing surfaces but separates completely from the surface at a sharp edge. This is a direct consequence of the inability of the fluid to undergo the very large accelerations required to follow the surface at the corners. Because of shear along the edge of the wake a return flow toward the body in the centre of the wake is induced. Thus, the characteristics of the wake region are (i) velocities much smaller than the mean flow, and, hence, almost uniform pressure on the body surfaces, (ii) a gentle flow upstream along the surfaces and (iii) a negative pressure compared to the ambient since it is dictated by the prevailing pressure at the point of separation. In addition to this mean flow there are intense pressure and velocity fluctuations resulting from the entrainment process along the wake streamline. It should be noted that these fluctuations are so large that the position of this streamline can be defined only by a long time average. Beyond this general description little can be said about the absolute values of c_p for a given body shape. In general, the location of separation depends on the shape and size of the body, the orientation and velocity of the wind but for bodies with sharp edges, i.e., for most buildings, the separation line is fixed along the edges. Hence c_p varies only with wind orientation for any given shape.

The surfaces of a structure exposed to the mean flow display a pressure distribution identical to that on a body in inviscid fluid flow with a free streamline for the wake streamline. Thus the pressure is above ambient over most of the frontal surface and there are steep pressure gradients near the edges where streamline curvature is sharp. For irrotational flows, e.g., in a constant velocity field, the pressure distribution can be predicted from theory but in many cases this requires a long, detailed calculation. For the boundary-layer velocity distribution, theory has not yet been developed, hence experimental measurements must supply the missing information.

There will of course be a thin boundary layer on these front surfaces. For the Reynolds numbers of model and full-scale buildings the thickness is of the order of 0.1 of the width of the building. The presence of this boundary layer does not affect the pressure distribution. However, since the velocity within the layer is small, it is influenced by the pressure distribution. Thus a secondary flow results along the surface of the body in the direction of the maximum pressure gradient. This fact can be used to predict the direction of the surface flow from the contours of c_p. Lines drawn normal to the contours thus are directions of secondary flow. Farther away from the body the streamlines are not in the direction of the pressure gradients because of the higher inertia of the main flow.

This discussion intimates the wide applications of the pressure contours such as are presented in *figs.2 and 3*. Some of these are

(i) evaluation of wind loads,

(ii) illustration of the direction of flow of pollutants released from the building,

(iii) determination of direction of surface motion of deposited rain,

(iv) general shape of snow drifts around building. This requires measurement of pressure distribution on the ground surrounding the building.

Such a list shows the practical advantages to be gained from any summarization of pressure distributions on building shapes.

3. EFFECTS OF A NATURAL VELOCITY DISTRIBUTION ON FLOW PATTERN

As a consequence of the preceding discussion it is to be expected that the potential flow and wake regions will be influenced in very different ways by changes in the velocity distribution in the approaching flow. Separation lines will obviously not be affected but the shapes of wake streamlines will be changed because of the change in the potential flow field. Thus the only change of significance to be expected on the body surfaces in the wake will be in the average level of c_p, because differences in the pattern of pressure contours will be small. On the other hand, the front faces will directly reflect the variation of stagnation pressure with height above the ground. Indeed, experimental observations reveal two flow phenomena not found in a constant velocity field. These are

(i) a secondary flow down the front of the body due to the fact that the pressure near the top is larger than at the bottom,

(ii) a reversal of flow along the ground in front of the body. This is the result of the adverse pressure gradient built up ahead of the body acting on the slower moving fluid near the ground. The result is a flow separation of a different kind on the ground at a point ahead of the body which involves a lateral flow away from the separation point to both sides. The size of flow reversal zone relative to the height of the building varies with the steepness of the velocity gradient, i.e., the ratio of stagnation pressures at the top and bottom and also with the height-width ratio of the building. The latter is an important parameter because the length of the zone of adverse pressure gradient is roughly equal to the width of the building. This upstream flow combines with the main flow on the front of the structure to produce the eddy sketched on *figs.7 and 9.*

The explanation of these phenomena by theoretical principles is straightforward, and similar reasoning can also be used to predict the effects on the pressure distribution. The secondary flows alone have little effect but the flow reversal and the consequent eddy give a zone of relatively constant pressure similar to the wake. This effect changes the pressure distribution over the entire front face. In a manner similar to flow in the wake, the size of the flow reversal zone fluctuates with time since the point of separation is not fixed by geometry. Thus large pressure and velocity fluctuations are found over the front surfaces.

The foregoing description of the potential flow zone was deduced from careful observation of a wall placed perpendicular to the flow. Examination of other wind orientations on the wall and the front faces of other shapes showed similar effects except that the size of the eddy reduced as the angle of orientation was decreased. In the interests of brevity this paper will be restricted to the 90° orientation, data and descriptions of other orientations being contained in other publications(4) (5).

In the following paragraphs the measured pressure distribution on some typical shapes will be discussed in detail and numerical values assigned to the effects described above. These can then be used to predict the pressure distributions on other shapes and provide rules for framing specifications.

4. WIND-TUNNEL TESTS OF PARTICULAR SHAPES

Description of Tests

Pressure measurements were made on models constructed of acrylic plastic sheet material in the low-speed wind tunnel of the Department of Mechanical Engineering, University of Toronto. This is an open-return tunnel with a 4 ft. by 8 ft. cross-section and a maximum speed of 25 ft./sec. Thus, although the pressures to be measured were small and required the careful use of micromanometers the results did not require correction for wall effects. The largest dimension on any model was 18 inches, and consequently any blockage effect was negligible. The methods and instrumentation used in the tests were conventional in wind-tunnel practice except in the creation of the velocity distribution. In every case a detailed measurement of the pressure distribution was made with the model in a constant velocity field. For this the model was set on a thin ground board mounted clear of the natural boundary layer of the tunnel floor. These results were taken as standard and agreed well with published data.

The boundary-layer velocity distribution was created in the lower half of the tunnel by installing a curved screen in the entrance of the test section. Considerable effort was expended in shaping this screen to produce the desired distribution. The final shape was roughly parabolic with the vertex upstream at the tunnel centre line. The top half of the cross-section was filled with a continuation of the screen normal to the flow direction. The action of a screen in producing a shear flow has been explained and a theoretical derivation presented by Elder(6). However, in the present instance it was not possible to calculate the resulting flow profile because of the interaction with the natural tunnel boundary layer and the large velocity deviation from the average. The velocity distribution evolved was described by the polynomial law used by Davenport(2).

$$\frac{V}{V_o} = \left(\frac{y}{y_o}\right)^{1/k} \qquad (1)$$

where V_o is the velocity at the reference elevation y_o. Most of the tests were conducted with a distribution for which $k = 4$. This corresponds to conditions on the outskirts of a large city. For a few of the earlier tests a different screen was used which produced a distribution for which $k = 6$. It was found that constant handling of this screen produced creases and wrinkles which acted like small lenses. Flow concentration resulted which could not be corrected and thus the screen had to be rebuilt.

Tall Buildings

Very clear evidence has been obtained[4] of the effects on a building of square floor plan with a height-width ratio of 8. This is typical of contemporary skyscrapers. All of the changes in pressure distribution between the two velocity distribution studies can be readily explained by elementary theory. These effects are best illustrated in *figs.2 and 3* which present the pressure contours for the wind normal to the front face. For this orientation the front face is in the potential flow region and all other surfaces are in the wake.

In the constant velocity field the pressure distribution on the front, see *fig.2*, is typical of that on a very long flat plate. The contours are vertical except near the top where over a length of about 2B (B = width) an end effect is displayed. In this area some of the mean flow deflected by the building passes over the end and some over the sides.

On the lower part of the building the flow deflection is entirely lateral and at the top the deflection is entirely vertical. In *fig.4* the streamlines close to the centre line are schematically presented. These were deduced from the pressure distribution and checked with tufts of wool held in the air flow. On the sides, roof and back of the structure the pressures are more uniform but still show gradients much larger than those found on low buildings[1]. Examination of the pressures in detail shows that the roof has more suction than the sides and back near the base. This indicates that the flow diversion over the top has resulted in more sharply curved wake streamlines. Since the wake is relatively stagnant an upward flow is induced from the relatively high pressure zone near the ground. The normals to the contours indicate that this takes place up the sides and back and into the roof zone from where the fluid is removed by the intense shear layer.

The patterns of pressure contours and flow lines are changed considerably in the presence of the velocity gradient, note *fig.3*. There is a strong downward flow and pressure gradient on the front, the pressures on the roof and sides are quite uniform and the roof pressure is about half the intensity of the constant velocity case. These can all be explained in terms of the variation of stagnation pressure with height on the front of the structure. In the region immediately upstream of any bluff body the flow must decelerate in the longitudinal direction and accelerate in the lateral direction for the fluid to pass around the body. Along the central plane this lateral acceleration must be small for reasons of symmetry, hence an area is developed on the front of the body where the pressure approaches the stagnation pressure

$$p_s = \rho \frac{V_o^2}{2} + p_o \quad \text{i.e., } c_p = 1.00$$

In the constant velocity case this is an area extending about 6B of the height from the base. The same tendency exists in the flow with a velocity distribution but the stagnation pressure varies with height. Thus the layer of air close to the surface is subjected to a strong vertical pressure gradient and a strong flow down the structure results as shown on *fig.4* for the streamlines near the central plane. As a result of the downward flow the velocity distribution is more uniform immediately behind the building. Thus smaller structures in the immediate vicinity would be subjected to higher wind loads than with the tall structure absent. This is a relatively minor effect, but the higher velocities on neighbouring streets would surely be noticeable, particularly by the movement of debris. Near the top of the building the downward flow is superimposed on the natural upward flow from the end effect. The result is a substantial reduction in the quantity of air flowing over the top and a reduction of the height influenced by the end. Consequently, the suction on the roof is reduced by about half. The effect of the velocity distribution on the pressure distribution near the top is the same as a reduction in height of the building. Thus it would be expected that the relative size of the reduction of suction on the roof would be larger for taller buildings and also for distributions with greater curvature. This is verified in observations on lower buildings. With the roof pressure reduced to the same size as that on the walls and back, the upward flows along these surfaces do not exist.

If it is assumed that a flow with a velocity gradient exists in thin, independent horizontal layers then a simple analytical solution is obtained for the pressure distribution. The pressure at any point is influenced only by the velocity in the main stream at the same elevation. Pressure coefficients are then determined from the equation

$$c_p = c_{p_o}\left(\frac{V}{V_o}\right)^2 \qquad (2)$$

where V = the velocity at the elevation where c_p is determined, and
c_{p_o} = pressure coefficient at the same point on the building in a constant-velocity field.

This assumption would be valid if the layer on the front of the body were so thin that the main stream were not affected by the downward flows shown on *fig.4*. This layer thickness has not been determined.

The overall accuracy of this linear approximation has been found by plotting profiles of the pressure distribution on the front face as measured and as predicted by Equation (1). *Fig.5* is the vertical profile on the centre line of the front face and this shows clearly the agreement found. Over the lower 75% of the structure, i.e., height equal to six widths, the agreement is very good. There is a small region of constant pressure at the base which is negligible for this case but which is a major factor in the pressures on low buildings. On the top section of height 2B the effect of the reduction in flow over the top is felt. The pressures are about 8% higher than those given by Equation (2). As shown by the vertical pressure contours in this region on *fig.3*, the deviated flow is to the sides. Thus the centre-line pressure excess is closer to $\varrho V^2/2$ than that given by Equation (2). Lateral profiles also show that these deviations from Equation (2) are generally found all across the width. Profiles for $y/H = 0.47$ show good agreement, those for $y/H = 0.735$ show deviations for part of the width and those close to the top show pressures all higher than predicted.

It is instructive to compare the deviations between total load on the front face as predicted by Equation (2) and as measured. The total load is about 3% larger than predicted but the total moment about the base is about 8% larger. Thus it would be expected that for all tall buildings this effect is of real importance.

A simpler approximation indicated from the above discussion is

$$c_p = c_{p1}\left(\frac{V}{V_o}\right)^2 \qquad (3)$$

where c_{p1} = a standard pressure coefficient given by the lateral profile for the uniform region in *fig.2*. A single lateral profile is specified and the pressure profile at any elevation is given by multiplying this by the local stagnation pressure. This means that along the centre line for 0° orientation the pressure coefficient is $(V/V_o)^2$. From *fig.5* it is seen that this gives good agreement up to within 5% of the top of the building. Similarly good agreement is found on the lateral profiles.

Pressure distributions on a surface in the wake region cannot be expected to be described by Equation (2) or (3). These pressures reflect conditions of separation all along the edges and thus are an integrated effect of the velocity distribution. For the equations it is assumed that pressure is determined by local conditions. An approximation to the wake pressures in a non-uniform velocity distribution can be obtained from the same general reasoning and the measurements in the constant velocity field. The average pressure in this case was influenced by the lowest i.e., the roof, pressure. Thus in a boundary-layer type velocity distribution, if the pressure coefficient at separation were constant, the pressure would be lowest where the velocity was highest. This would make the roof pressure the controlling factor again but as noted above, the roof pressure is affected by the reduction in flow up the building at the top. Consequently the measured reduction of 40% on pressures is consistent with these arguments. Extending this reasoning to the general case leads to the conclusion that average pressure coefficients should decrease with building heights and the relative reduction of c_p by a non-uniform velocity distribution should also decrease. These have been observed.

Low Buildings

The classification of a building as low or high in relation to the pressure distribution on its surface is through the ratio of height to width of the frontal projection. Absolute height is relatively immaterial compared to this ratio in influencing pressure distribution because this is primarily the result of top and side deflection of the main flow streamlines.

(i) Very Wide Wall

This case of a low building demonstrates the opposite limit of effects to the skyscraper. Flow around the sides of the wall is negligible compared to that over the top. Thus for most of the width the flow is essentially two-dimensional and a single curve presents the pressure distribution.

In a constant velocity field the wide wall is subject to the same flow conditions as a long flat plate submerged in an infinite fluid. The plane of symmetry of the plate corresponds to the floor on which the wall rests and the streamlines and pressure distribution shown on *fig.6* are thus obtained. On the front there is a more gradual decrease of pressure from the base to the top than on a tall building, note *fig.5*. On the rear the constant suction of the wake is seen. The value of -1.4 shown for c_p was measured(7) for an infinitely long plate. This changes with height-width ratio, being about -1.0 for a ratio of 0.1.

The flow pattern and pressure distribution in a boundary-layer velocity field shown on *fig.7* have been deduced from measurements on a wall with a height-width ratio of 0.5 and corrections made for end effects. A stable eddy with a horizontal axis forms along the front of the wall at the base. This eddy is roughly circular and the size depends primarily on the curvature of the velocity profile. The more curved the profile, i.e., the smaller the value of k in Eq. (1) the larger the eddy. It forms as a consequence of the adverse pressure gradient ahead of the wall due to stagnation on the wall. A return flow is set up along the floor in response to this pressure gradient because the inertia of the fluid particles near the floor is very small. Because the pressure throughout this eddy is virtually constant the pressure variation over the front of the wall is small and the load on this surface is greater than for a constant velocity field. It appears that the suction in the wake is also not so large because of the same effects which lead to a smaller roof pressure on a tall building in the boundary-layer case. Thus the total load on the wall is reduced in the presence of the boundary layer but by a relatively small percentage. Available results indicate that this reduction is about 10% for a velocity field typical of an urban area. However, because of the uniform pressure on the front the overturning moment about the base of the wall is increased by a small percentage in the presence of the boundary layer.

(ii) Wall of Height-Width 1:1

For walls with the height and width of the same order the flow pattern shows the effects of deflection over both the top and the sides. It is thus a combination of the two simplified cases discussed above; the distribution of pressures varies considerably with height-width ratio. No general conclusions can be drawn applicable to all ratios but trends due to the top and side effects can be seen in the measurements. *Figs. 8 and 9* present the flow pattern and centre-line pressure distributions for the constant velocity and boundary-layer fields respectively. Nothing unusual is seen in the first figure but with a velocity gradient the pattern reflects the phenomena discussed above. The effect noted on the tall building of pressure varying with free-stream stagnation pressure is also found but only over the upper portion. The lower part is covered with the eddy found in front of a very wide wall. The length of this eddy is so short that there is very little recirculation and near the sides the streamlines are entirely lateral. Thus the flow near the wall in this area exhibits the same downwash noted for the tall building. Again the structure acts to bring high velocity air to lower levels. The effect of the eddy is most clearly noted on the floor where a dividing streamline exists. In the layer adjacent to the floor the air downwind of this streamline is moving away from the building and upwind of the streamline toward the building. Thus any material moved along the floor tends to deposit near this streamline in the zone of minimum velocity. A good example of this dividing streamline is the snow drift ahead of a building which accumulates during a high wind. There is always a clear area in the front of the building. From the arguments above it is evident that the size of this area depends on the height-width ratio of the building and the curvature of the velocity profile.

In both velocity fields suction in the wake is much smaller than for the wide wall. There is also little difference between the suction in the two cases. In addition the suction is less than that found on tall buildings, indicating that the wake pressure is least negative for ratios near unity. This is consistent with observations of flat plates in infinite wind streams(7).

(iii) Rectangular-Block Structures

From the preceding discussion it is evident that the effects of velocity distribution on the flow around walls are readily explained and predictions can be made of the pressure distribution on walls of any shape in any wind at any orientation. The only point which remains to be settled in predicting the wind loads on building shapes is the influence of velocity distribution on the side, roof and back surfaces of a building. Because of the separation along front edges the pressure distribution on the front is independent of the depth of the building, i.e., dimension in the flow direction. For wind directions other than the normal incidence, the pressure distribution over the front may vary with length of side walls but the effect of velocity distribution on the pressure distribution is the same as for thin walls.

Measurements of pressure distribution on a cube are typical of all rectangular-block structures. These show the complexity of flow in any velocity field and demonstrate that no simple conclusions about the wake pressures can be drawn. *Figs. 10 and 11* present measured pressure contours for the constant velocity field and a boundary-layer field typical of a suburban area.

Front surfaces exhibit a distribution virtually identical to that measured on a wall of a 1:1 ratio. These are typical of all block structures of similar height:width ratio. On the sides and the roof the suction is slightly greater in the boundary-layer flow and the pattern is quite different. This change is consistent with the differences found in the suction on the rear, i.e. in the boundary-layer flow the suction is much less than in the constant-velocity field. For other structural shapes and wind directions the results were quite similar but some cases have been found in which the differences in pressure distribution between the two velocity fields were very small. The variations are not easily explainable and no doubt are due to the complex nature of the flow in the wake. For example, along the sides the wake is restricted in width by the solid wall. Thus the flow which separated on the front edges may become reattached ahead of the rear edges. This area of reattached flow depends on the velocity distribution as well as the shape and orientation parameters. There is reason to believe that it may also depend on the Reynolds number of the flow, hence the small-scale model tests may not define the pressure distribution on a building. However, the average pressure on the sides and roof is not likely to vary much with a change of Reynolds number of 100 or 1000 fold.

From the results shown on *figs. 10 and 11* and measurements on other rectangular-block structures it appears that the soundest recommendations which can be made at present are maximum suction coefficients applicable to any conditions. For the wind normal to one face these would be a pressure coefficient of -0.55 for the rear surface and -0.70 for the sides and roof.

(iv) Structures with Gable Roofs

Measurements have also been made of the flow pattern and pressure distribution around a cube with a series of gable roofs [5]. In every case the effects of the velocity distribution were identical to those observed

(ii) below this elevation the lateral pressure distribution is relatively constant with height: the distribution is approximately the same as that determined by (i) above at elevation equal to the width,

(iii) if the building is much lower than the width, a constant value of $c_p = 0.9$ provides a conservative loading over the whole front face for a perpendicular wind. At other wind orientations the values listed in building codes suffice.

For the side and rear faces of a building the pressure coefficients given by standard wind-tunnel tests should be used. In some cases it may be possible to reduce the design loads but this rarely exceeds 10%.

For the roof the pressure coefficients can be reduced by up to 50% for a tall building, (height - width ratio = 8) but for a building of ratio = 1 the pressure should be that for a constant velocity field.

Probably the most important conclusion of the studies has been that c_p varies relatively little from the values listed in building codes provided that it is based on the natural velocity at the elevation of the top of the building. This means that the average wind pressure is a function of the height of the building. This is consistent with the observation that a building in a natural wind field acts as a deflector bringing high energy air down to lower levels. Thus neighbouring low structures are subjected to higher velocities and ground level winds increased in magnitude.

In addition to the total loads on walls discussed above, there is considerable practical interest in local high pressures which dictate loads on windows, fasteners and similar small items. A few of these situations have been studied and in no case was a consistent intensification or relief of the condition noticed. Thus, for example, closely spaced buildings of comparable height should be designed for constant velocity conditions.

It is apparent that wind loads on all building shapes are as complex in description as the shapes themselves. This complexity is considerably reduced if the designer is familiar with the characteristics of flow around bluff bodies and can use this knowledge in his deductive process. The prime object of this paper has been the supplying of such knowledge for the case of a natural wind field.

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on walls and rectangular-block structures. This is not surprising since the roof is located in a region of relatively small velocity gradient. Such a conclusion would not be expected for changes made to the building shape near the ground.

(v) Structures of Intermediate Heights

A progressive change in effects was noted in comparing the pressure distributions on walls for height-width ratio varying from 1 to 8. As the building height increased the size of the frontal eddy remained roughly equal to the width of the building. Thus the pressure distribution above a height equal to the width could be accurately predicted by the schemes used for the tall building. Below this level the pressure is roughly constant. In the wake region the effects of velocity distribution varied from those observed on the cube to those on the tall building.

5. APPLICATION TO BUILDING DESIGN PROBLEMS

Phenomena associated with the gradient of wind velocity have been observed and analyzed from the wind-tunnel studies of small building models. These same effects must occur on full-scale buildings but it would not be expected that the identical pressure distribution would be found. Buildings differ greatly from models in surface finish and appurtenances which particularly influence the line of separation and wake suction. Furthermore the Reynolds number of the flow over the building is up to 500 times that over the model. This means that the areas of flow reattachment will be much different in the two cases. In opposition to these considerations are the facts that forces due to steady winds on any structure need not be predicted within a few percent and the detailed pressure distribution is rarely required. Thus the general rules deduced by comparing the pressure distributions in constant velocity and boundary-layer wind fields should be of sufficient accuracy for the prediction of wind loads in the majority of cases. For buildings of peculiar shape or location either a more careful analysis based on the complete test results[5] or a model test will be required.

It is possible, therefore, to formulate a few simple rules for the prediction of wind loads on a building with flat surfaces in a natural wind field. It is assumed that the pressure distribution determined from a standard wind-tunnel test is known. For the front surfaces:

(i) above an elevation equal to the width of the building the pressure coefficient c_p can be accurately predicted by multiplying c_p for a long flat plate at the same point by $(V/V_o)^2$ where V_o is the undisturbed velocity at the top elevation of the building,

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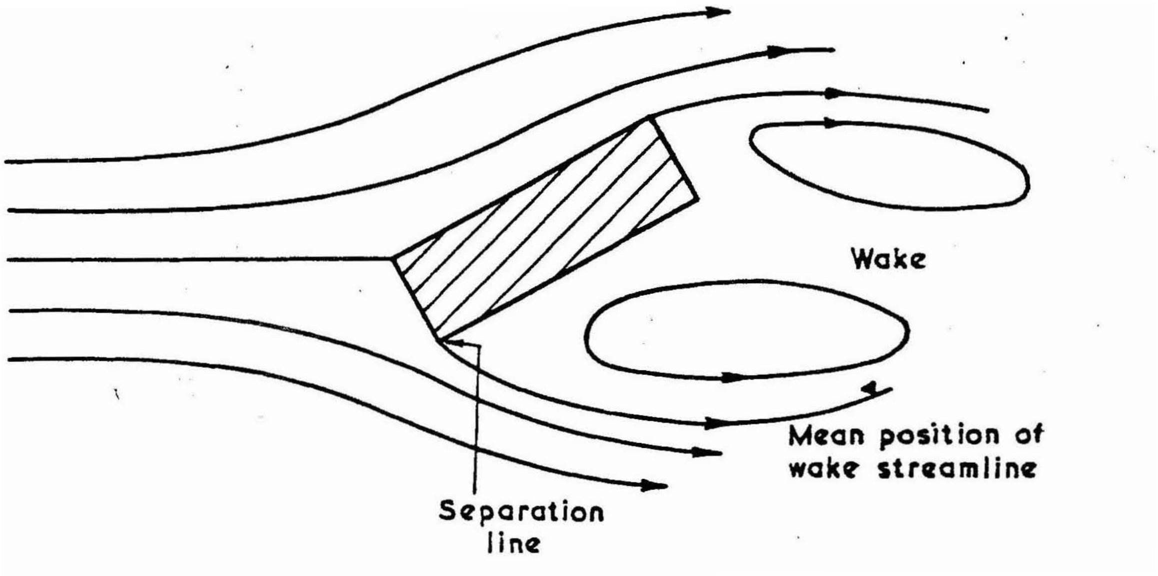

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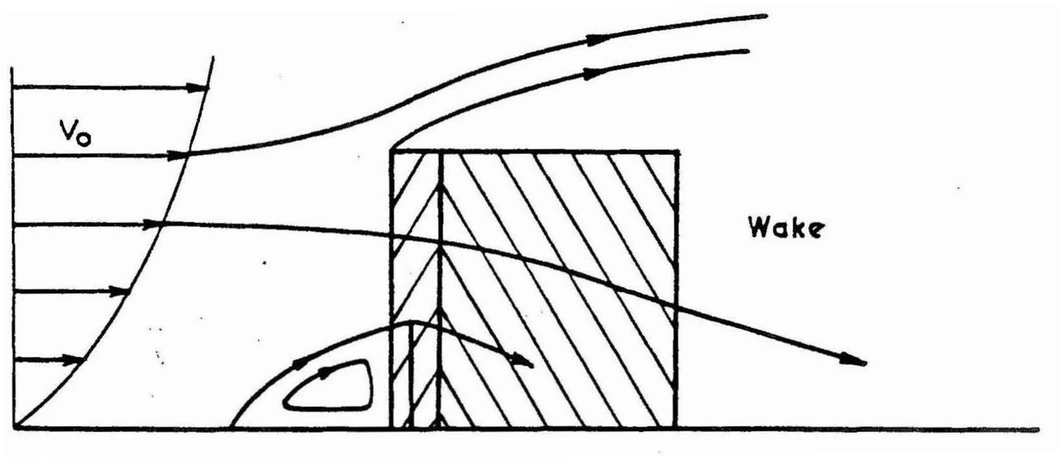


Elevation

Fig.1. Definition Sketch of Flow over a Building

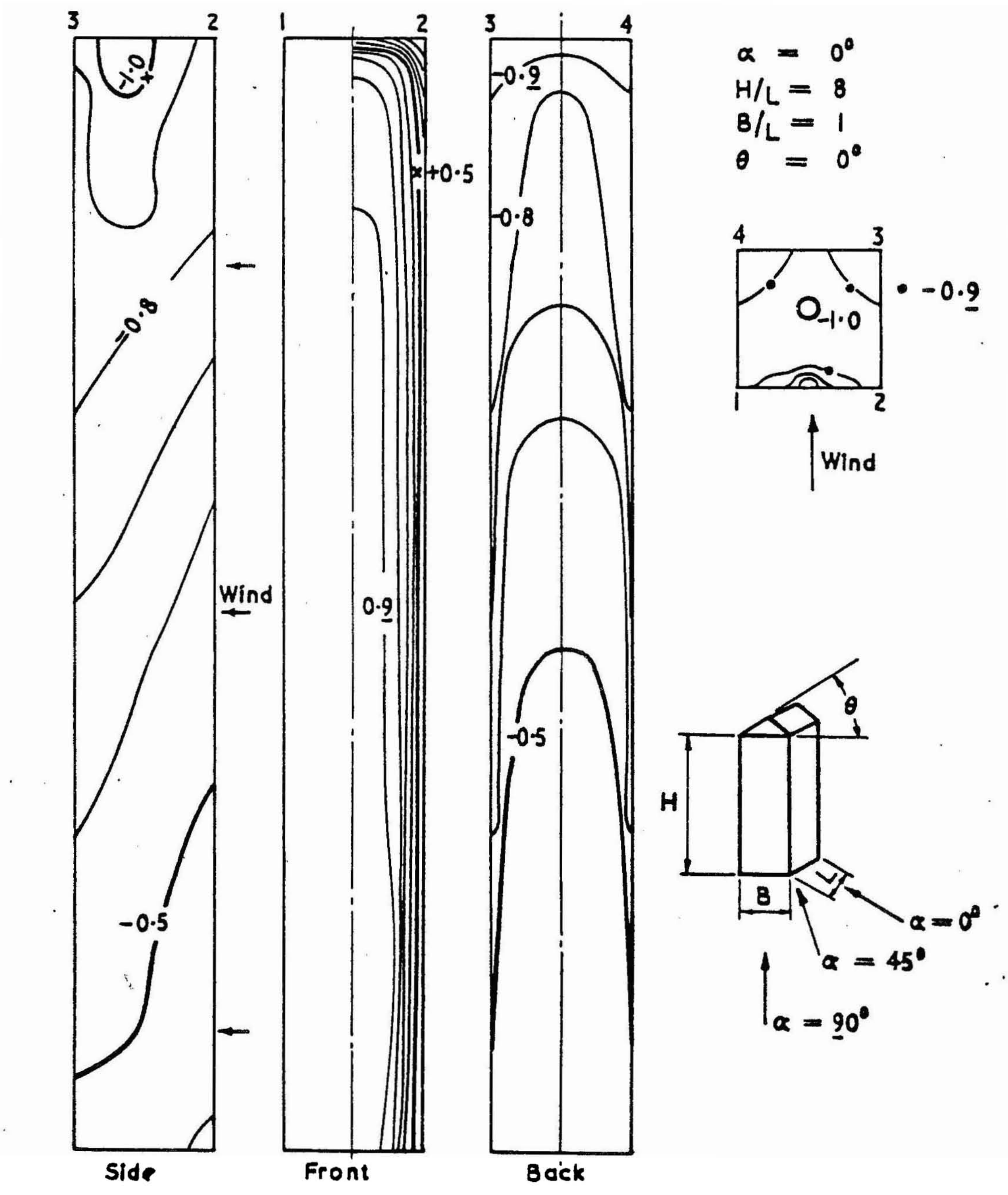


Fig.2. Pressure Distribution, Tall Building in a Constant Velocity Field

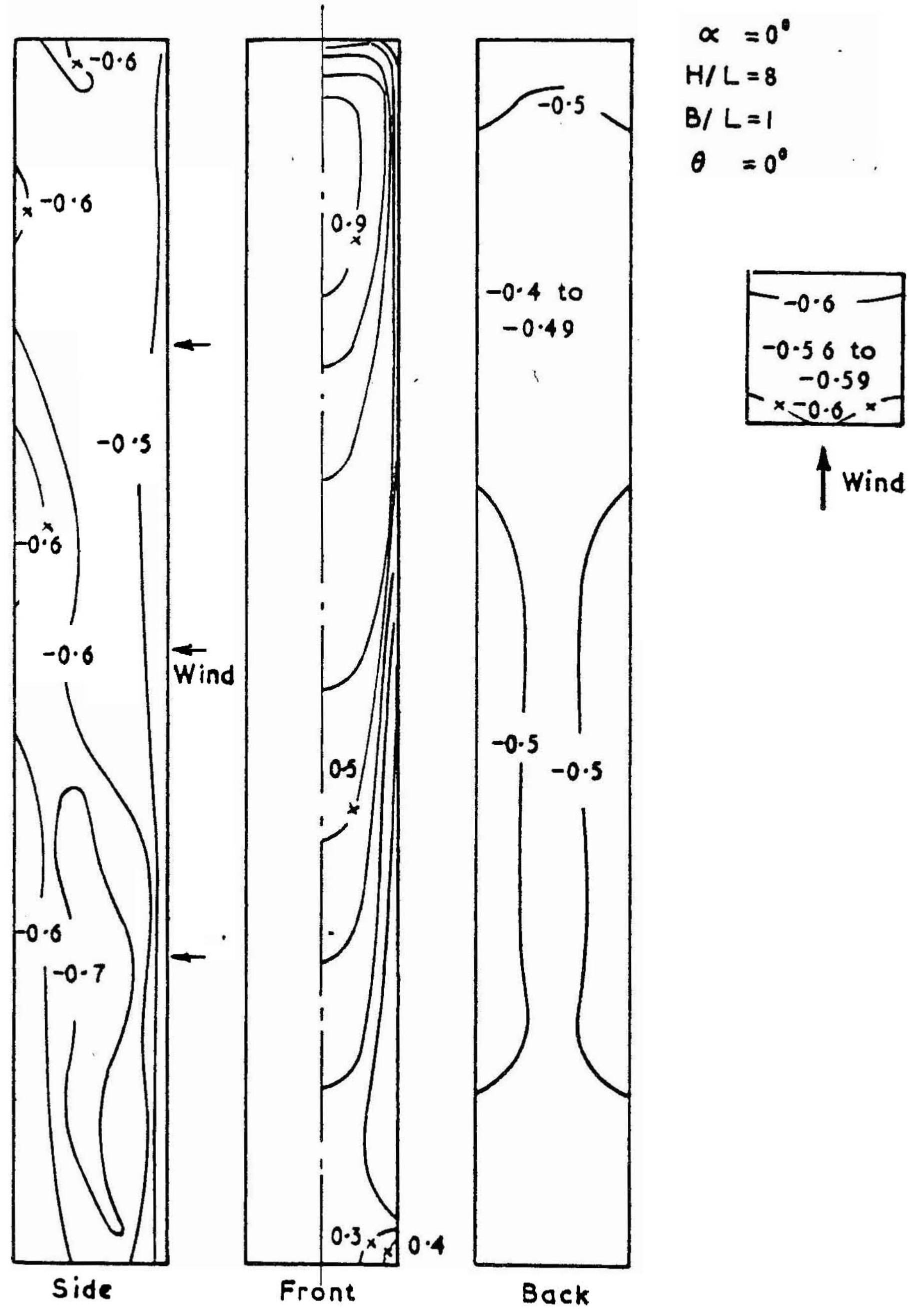


Fig.3. Pressure Distribution, Tall Building in a Boundary-Layer Velocity Field

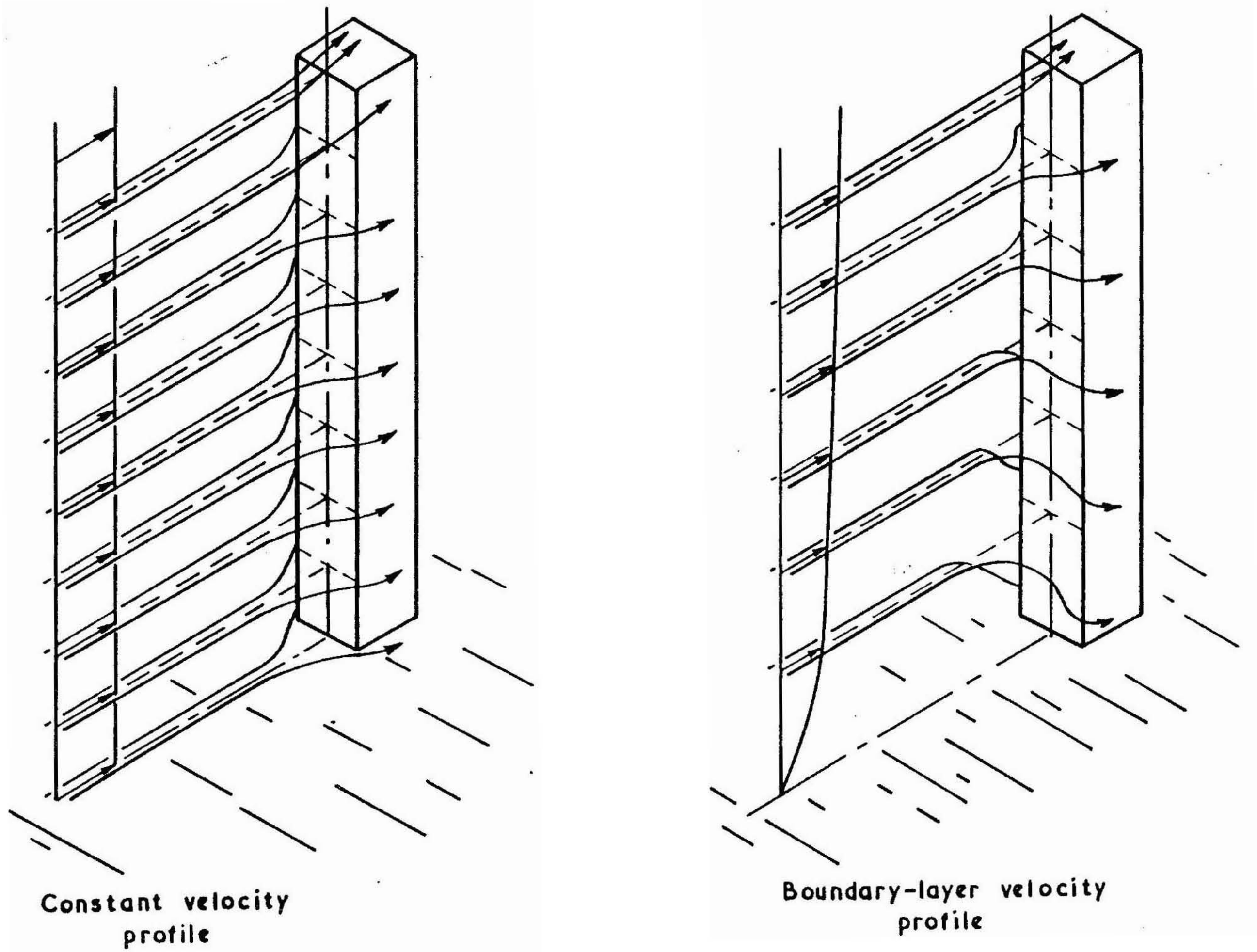
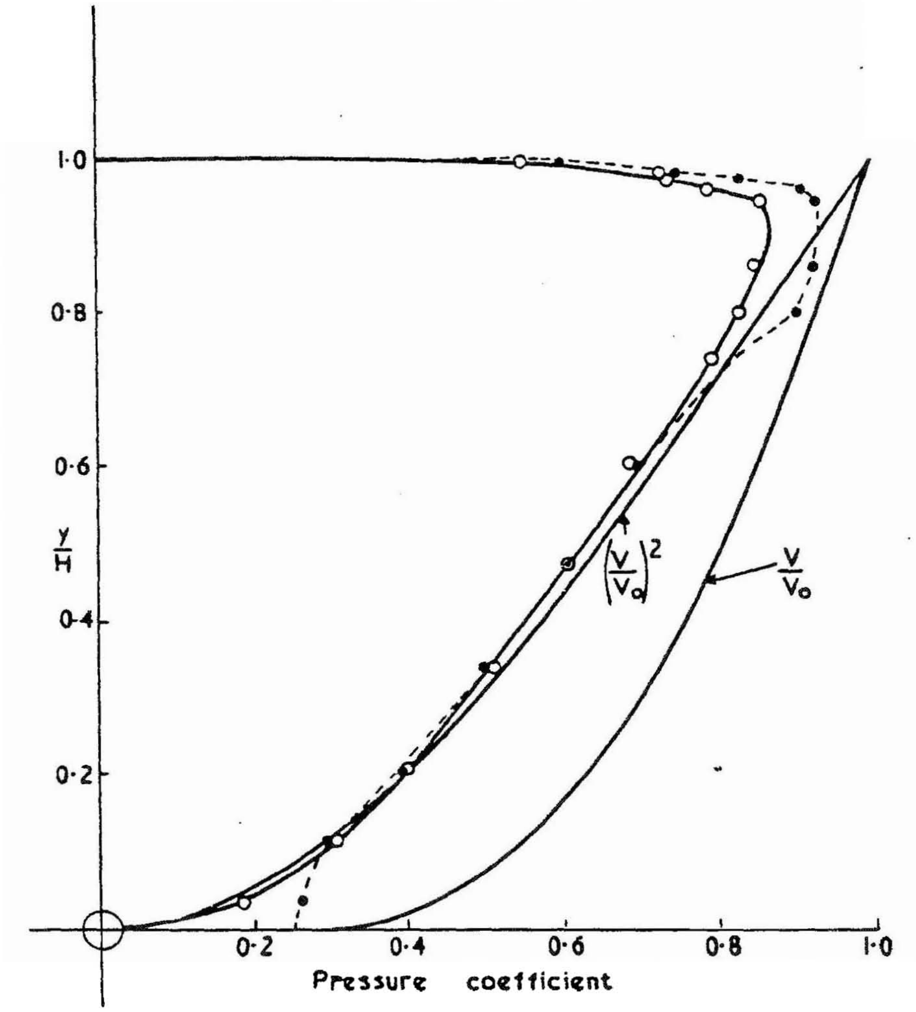


Fig.4. Tall Building, Sketch of Streamlines near Central Plane



• Measured (model immersed in boundary layer)

○ $\left.\frac{\Delta P}{\frac{\rho V_o^2}{2}}\right|_{unif.} \times \left(\frac{V}{V_o}\right)^2$

V_o = Reference velocity

Fig.5. Tall Building, Pressures on Front Centre Line, $\alpha = 0^o$

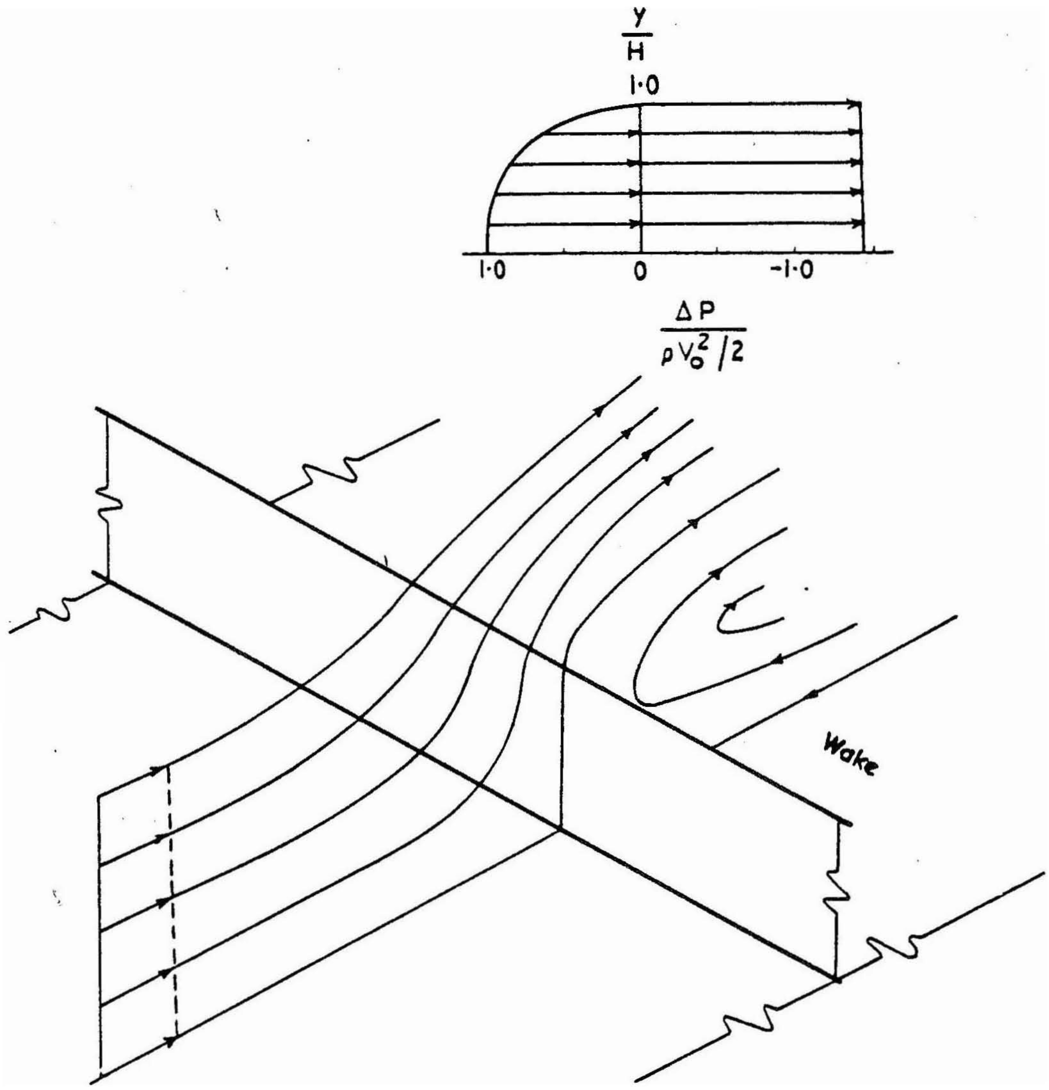


Fig.6. Flow Pattern and Pressure Distribution - Very Long Wall in a Constant Velocity Field

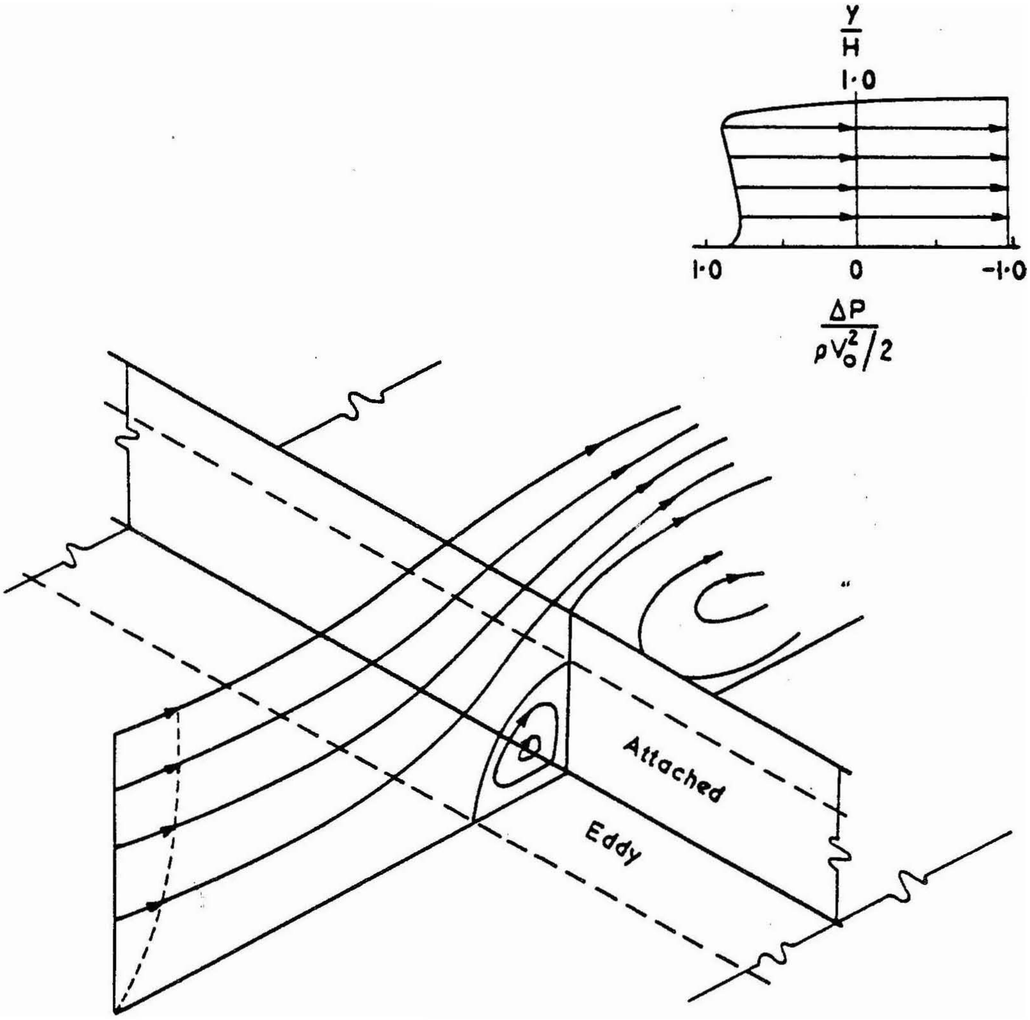


Fig.7. Flow Pattern and Pressure Distribution - Very Long Wall in a Boundary-Layer Velocity Field

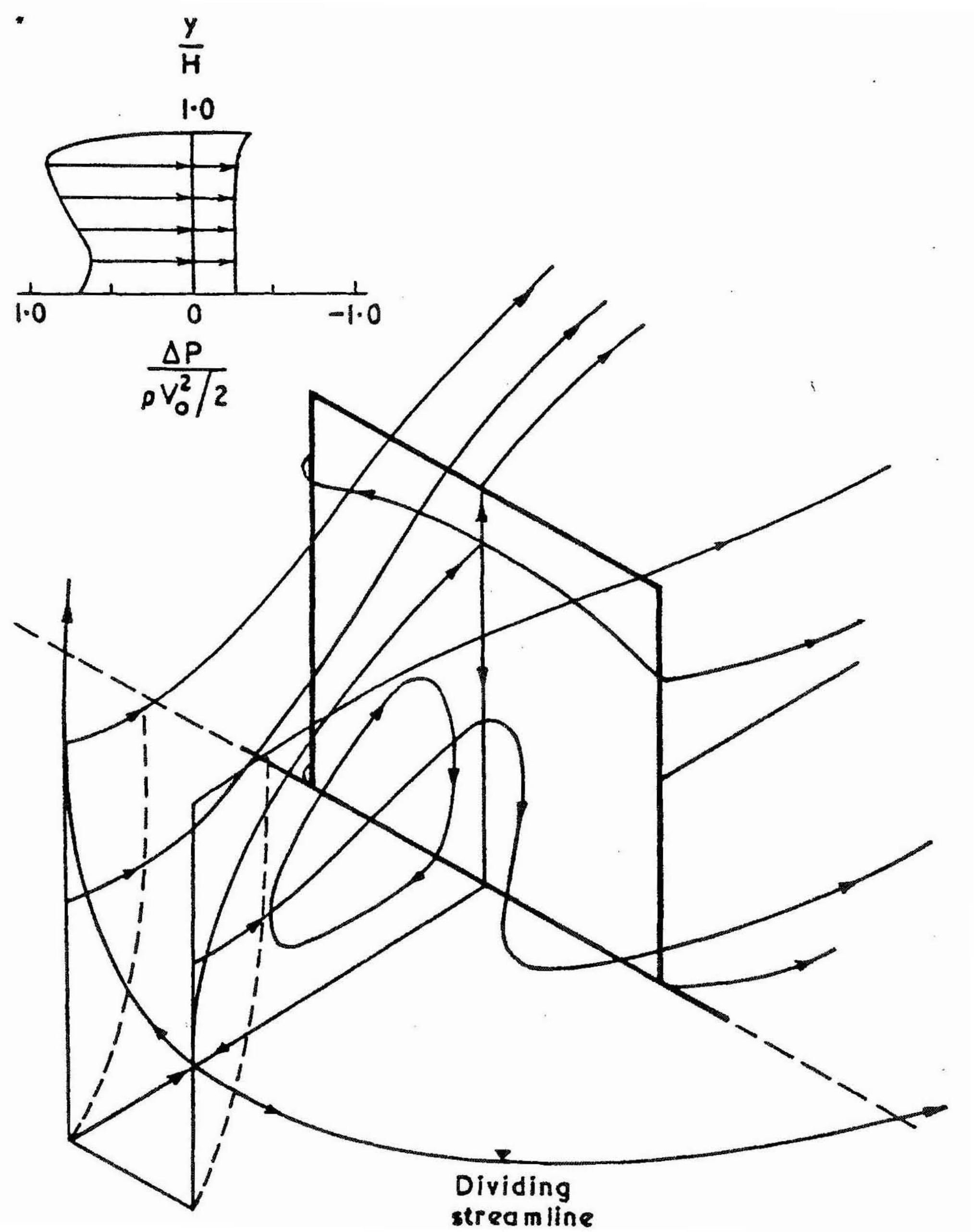


Fig.9. Flow Pattern and Centre Line Pressure Distribution -
Wall of Height: Width = 1:1, in a Boundary-Layer Velocity Field

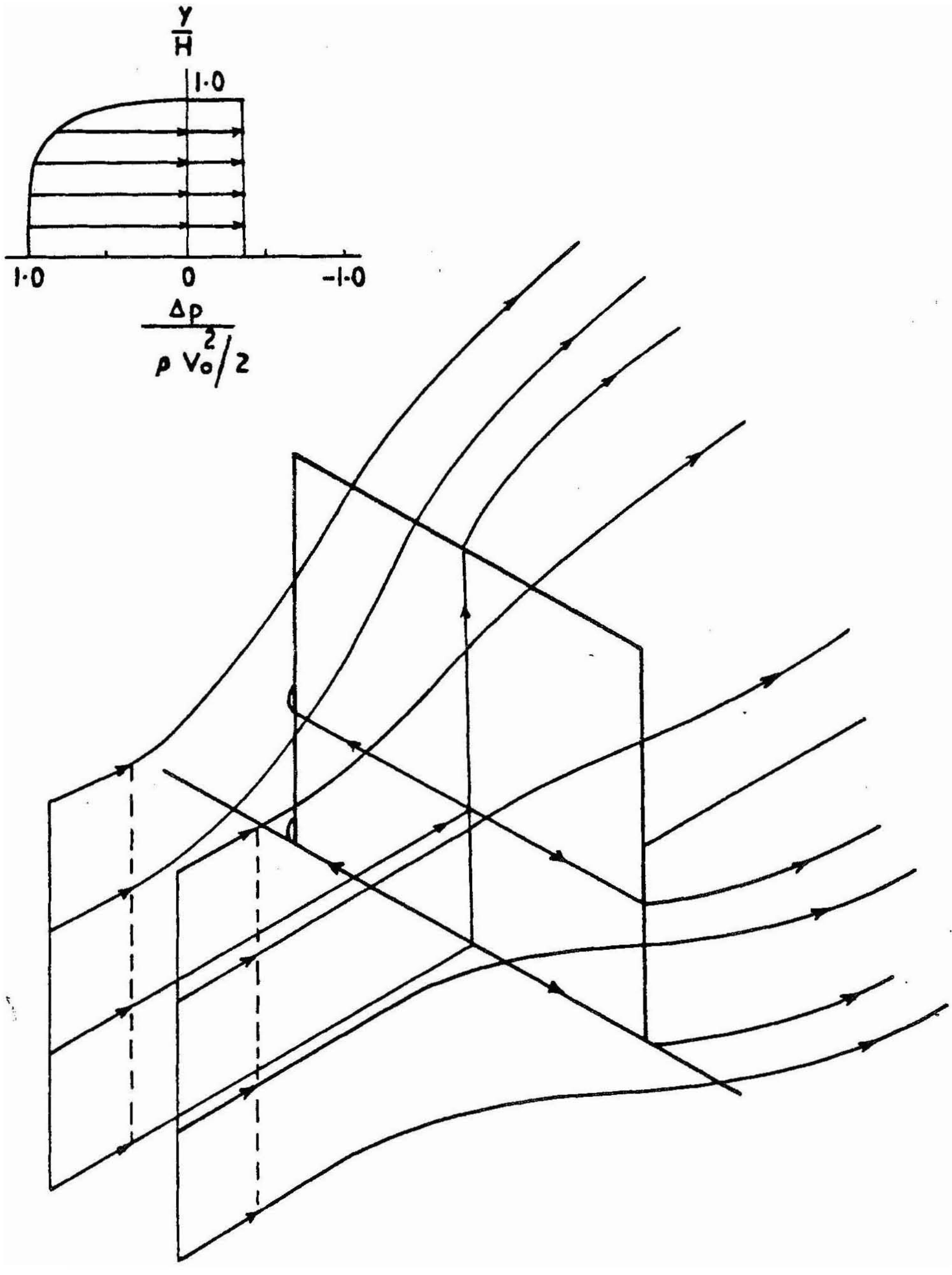


Fig. 8. Flow Pattern and Centre-line Pressure Distribution -
Wall of Height: Width = 1:1, in a Constant Velocity Field

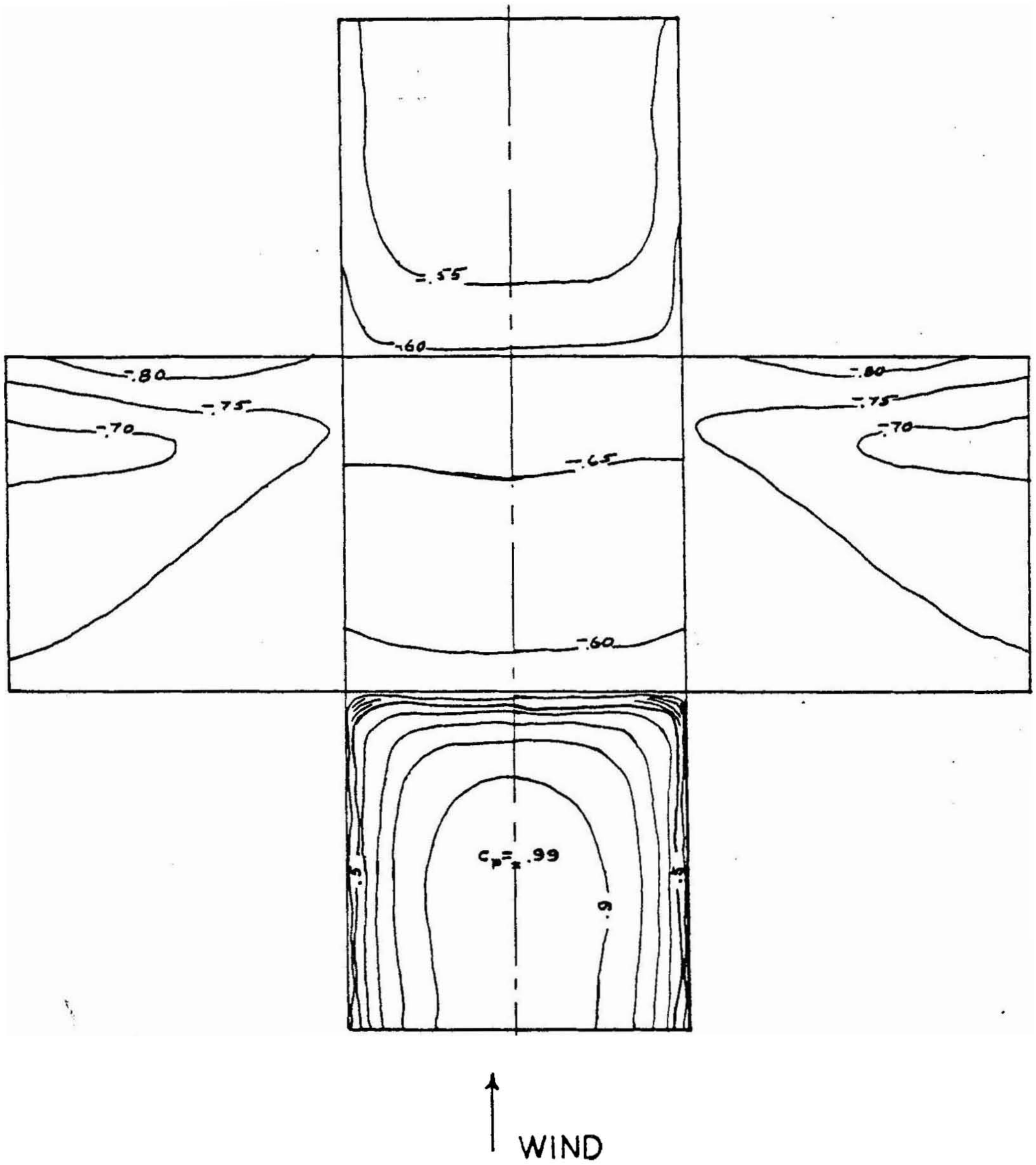


Fig.10. Pressure Distribution on a Cube in a Constant Velocity Field

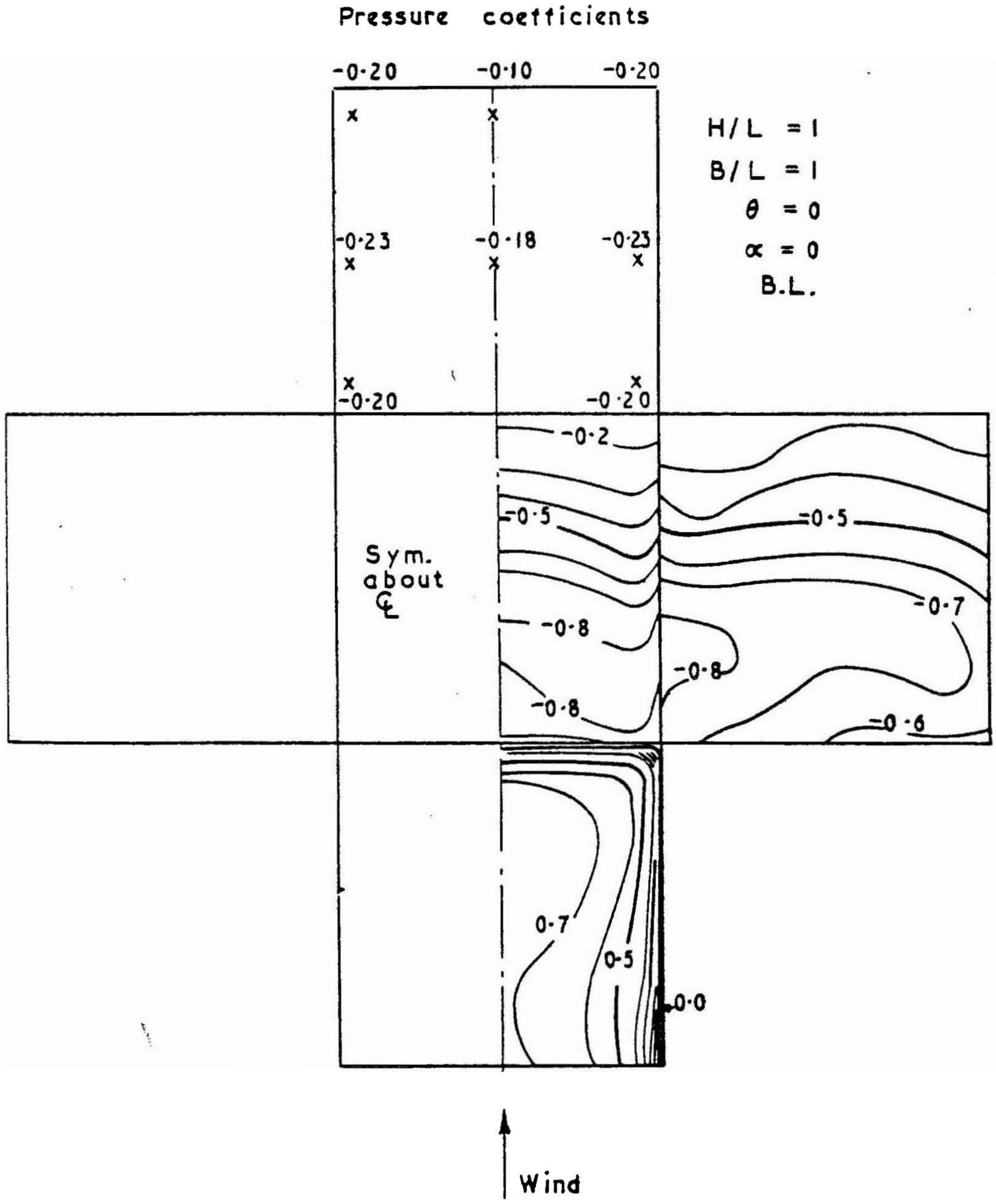


Fig.11. Pressure Distribution on a Cube in a Varied or Boundary-Layer Velocity Field

DISCUSSION ON PAPERS NOS. 15 AND 6

MR. WISE asked for information on how the distance upstream of the screen, used by Professor Baines to produce a velocity profile, was related to the dimensions of the model. He similarly enquired from Mr. Franck of the distance upstream it was necessary to reproduce the local terrain. The downwash in front of a tall building found by Professor Baines had a practical manifestation in Notting Hill Gate where the resultant increase in wind speed in front of a recently built tall block had caused serious inconvenience to pedestrians.

DR. PRIS thought that it was important to resolve the differences between the two schools of thought among wind-tunnel experimentalists; between those who consider that it is necessary for reliable results to reproduce the wind gradient, and those who believe that such results are better obtained without a simulated wind gradient.

PROFESSOR DAVENPORT said that while Mr. Franck had succeeded in producing a turbulent wind stream in the tunnel, he apparently did not measure the resulting fluctuating pressures. Were the pressures presented maximum or mean values? Professor Davenport felt that to achieve similarity with the actual turbulence was a very formidable task indeed. The scale of turbulence at most structural heights was enormous; for instance, the horizontal scale of mechanical turbulence probably approaches 4,000 ft. which, when scaled down to a model scale of 100/1, represented eddies of about 40 feet in the wind tunnel.

Professor Davenport enquired of Professor Baines whether the higher energy of the flow at the top of the building was more significant than that of the velocity meaned over the height of the building; that is, should the velocity at the top, or at half-height, be used?

MR. NEWBERRY agreed with Professor Davenport's remarks on the reproduction of turbulence in wind-tunnels, and enquired of Mr. Franck whether any measurements had been made of the dimensions of the gusts produced in his wind-tunnel. In his full-scale work it had been found that the incidence of wind could change through 140 degrees within a few seconds.

PROFESSOR PAGE claimed to have evidence from the field to support the conclusion of Professor Baines about the downward flow on the windward faces of tall buildings, and he supported this view with illustrations on slides of several incidents which occurred in the Sheffield area during the gales of February, 1962.

MR. FRANCK (in reply) said that the wind tunnel in Copenhagen had an experimental section 7 metres in length and all of this was fitted with the appropriate roughness coating. The boundary layer thickness produced by the tunnel surface should be twice as thick as the height of the model. No measurements of fluctuating pressures due to the turbulence produced in the wind tunnel had yet been attempted.

PROFESSOR BAINES (in reply) said that the distance upstream of the curved screen he used for producing velocity gradient in the wind tunnel was quite short; otherwise the effects of the smoothness of the tunnel floor became evident. In reply to Dr. Pris' question on the necessity for a velocity gradient he said that it depended on the dimensions of the structure under test. For example, the effect of a velocity gradient on a skyscraper was to reduce the load on the roof by as much as a half. On a low building, say four or five storeys, the velocity distribution had no effect on the roof suction. Professor Baines agreed with Mr. Franck that the relevant wind speed was that at the top of the building. The wake pressure is related to the speed at the top of the building. The higher the building the higher the suction not only at the top of the building but also lower down to ground level. On the problem of interference effects on groups of buildings he had found that certain spacings of buildings could produce greater than normal suctions and pressures, but the effects of velocity gradient on these proximity effects was extremely small.