NATIONAL BUREAU OF STANDARDS REPORT

10 476

A DEMONSTRATION WIND TUNNEL FOR BUILDING RESEARCH

U.S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

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A DEMONSTRATION WIND TUNNEL FOR BUILDING RESEARCH

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Summary

A wind tunnel specially suitable for demonstrating wind-building interaction has been constructed at the Structures Section, Building Research Division, IAT, National Bureau of Standards. The main purpose of this wind tunnel is to promote comprehension of the complex problem of wind loadings on buildings. The specification, design, and construction are discussed. The close-circuit wind tunnel has a test section 1.5 ft. x 1.5 ft. x 3.5 ft. The ceiling and side walls of the test section are made of "lucite" plexiglass, whereas the floor is made of 1.5 in. thick plywood. This furnishes convenience for observation. Wind speeds from about 5 to 55 fps are given by a variable speed D. C. motor. The wind tunnel was built by the Structures Section's own labor force.

The first series of studies that were made used a rigid model and visualization technique. Under various approaching wind directions, flow separation and reattachment, vortex formation, and flow patterns around the model are clearly demonstrated. The effects of these phenomena on wind loadings are also discussed.

TABLE OF CONTENTS

Page

Summary i

1. Introduction 1

2. Design and Construction of the Tunnel 2

   2.1 Test Section 3
   2.2 Entrance Section 3
   2.3 Honeycomb and Screen 4
   2.4 Corners 4
   2.5 Fan and Motor 5

3. Calibration 5

4. Demonstration of Wind Flow Patterns Around a Building Model . . . 6

   4.1 Some Considerations of Building Modeling 7
   4.2 Near Two-Dimensional Flow Over a Low Building 8
   4.3 Flow Separation and Reattachment 10
   4.4 Vortex Formation on a Building Model 12

5. Conclusions 13

6. Acknowledgements 14

7. Reference 14

1. Introduction

With the current developments in new structural materials, modern architectural concepts, and trends towards larger windows and thinner cladding panels, the understanding of wind effects on buildings becomes more important if the structure is to be safe and functional. Consequently, a combined effort of industrial aerodynamicists, structural engineers, and climatologists is urgently needed to develop reliable methods for the estimation of wind loads on buildings. The flow-building interaction problem is very complicated with the presence of flow separation, flow reattachment, vortex formation, and wake influence. In addition, building shape is not always in simple geometric form. Hence, when analytical treatments are inappropriate or become too complex for supplying answers to such problems, wind tunnel model testing and full scale measurements are the most promising approaches. The model study offers particularly attractive features; it gives the aforementioned specialists the accessibility to solve parameters involved in the problem in a quick and controllable way. Moreover, the model study furnishes vital wind loading information for the design of the prototype. This is the purpose of constructing a low speed wind tunnel.

The available space in the Structures Section, Building Research Division, NBS is inadequate to have a sizeable wind tunnel. The tunnel is to be accommodated in a room with floor area 10.5 ft. x 16 ft. Furthermore, one side of the room is used for other purposes. Therefore, this wind tunnel is not designed for detailed simulation of the atmospheric boundary layer, the surrounding topography and structures. It is rather designed to show the flow characteristics around scaled rigid or aeroelastic models

and their static or dynamic response under wind action.

This wind tunnel is a closed circuit type and has a test section 1.5 ft. x 1.5 ft. x 3.5 ft. Wind speeds from about 5 to 55 fps are given by a variable speed, one horse-power D. C. motor. This wind-tunnel is expected to show qualitative results, and hence the name of the wind tunnel is a "demonstration" wind tunnel.

In this report the general consideration, design and construction of this wind tunnel are discussed. Its use is illustrated by a series of studies made with a rigid model using a visualization technique. Under various approaching wind directions, flow separation, reattachment, vortex formation, and flow pattern around the model are clearly demonstrated. Their influence on wind loading is also discussed. This rigid model is scaled down 1:400 from a full-scale building which was investigated by Marshall and Hsi [1].

2. Design and Construction of the Wind Tunnel

The severe limitation imposed on the design of this wind tunnel is that it should fit one side of an existing room having a floor space of 10.5 ft. x 16 ft. First consideration is, of course, how to move the completed sections of the wind tunnel through the door and to assemble them in the room. Secondly, how large the test section (demonstrating section) should be in order to accommodate a reasonably large model without severe flow blockage effect. It is also important that the model should be placed at the height convenient for observation. In addition, the wind speed should be continuously variable over a range of about 5 to 55 fps, the wind tunnel air stream should be free from excessive turbulence and local velocity irregularities, and models should be readily accessible when the

tunnel is in operation.

The design shown in Figure 1 was evolved with the above requirements in mind. The tunnel was built by the Structures Section's own labor force. The overall view after completion is given in Figure 2. Wind tunnel design criteria of Bradshaw and Pankhurst [2], Sexton [3], and Pope [4] were used in the design of this wind tunnel.

2.1 Test Section

The test section has a nominal cross-section of 1.5 ft. x 1.5 ft. and a length of 3.5 ft. Its ceiling and side walls are made of "lucite" plexiglass, whereas the floor is made of 1.5 in. thick plywood. On the floor a removable and rotatable wooden disk is mounted flush with the floor surface. Models are to be placed on the disk, and hence they are rotatable while in testing. Owing to the size of the test cross-section, the projected area of a model should be no larger than 16 square inches in order to hold the flow blockage effect within five percent. One side wall of the test section can be removed by opening four latches fastened to the top, as shown in Figure 2.

2.2 Entrance Section

The contraction nature of the entrance section prevents flow separation, and hence the shape of the section is not critical. Curves producing either sinusoidal or constant acceleration of the air are satisfactory, as are almost any smooth curves. In general the upstream part of the entrance may contract abruptly, but the downstream part should be changed gradually so that the flow has time to even out. Pressure rising rapidly enough to cause separation should be avoided.

The entrance section of this wind tunnel consists of four pieces of curved fiberglass plates. Wooden ribs are used along edges of these plates. The contraction ratio is 2.78. The length of this section is 30 in., see Figure 1.

2.3 Honeycomb and Screen

The honeycomb and smoothing screen are used to ensure that the airflow is parallel to the axis of the wind tunnel and free from large scale turbulence. The honeycomb used in this tunnel is made of aluminum foil, with hexagonal cells 3/8 in. across flats and 4 in. thick. The cell structure is adequate for the purpose required. The honeycomb is installed before the turning corner which, in turn, is connected to the entrance section. This arrangement furnishes more space for the design of the entrance and test section.

Three stainless steel, square mesh wire screens are mounted on a wooden frame and installed before the entrance section. The screens are of 20 meshes per inch with wire diameter 0.009 in. and open area of 67.2%.

2.4 Corners

Closed-circuit tunnels need cascades of vanes to turn flow smoothly in 90 degree corners. The flow phenomena at the corner, with and without turning vane, are illustrated in Figure 3. The eddies generated in unvaned corners amount to a large loss in pressure head. In this wind tunnel, the galvanized steel blades turning vanes are used for its four corners. These steel blades are double walled and formed to assure that any point on one blade is equidistant from the same point on an adjacent blade. This precise blade shape maintains constant duct area and assures constant

air speed around the corner, eliminates loss due to speed changes, and results in low friction loss. For wind speed 20 fps, the pressure loss is 0.04 in. of water with turning vanes, but is 0.19 in. of water for no vanes.

2.5 Fan and Motor

Estimation of pressure drop for the fan specification may be made once the design of the major sections of the wind tunnel is decided. Pressure drop is estimated in terms of the loss in dynamic pressure $q = \rho v^2/2$ through individual items. The values for loss of the honeycomb, screen duct skin friction, corners, diffusers, and entrance section are estimated from those recommended by Sexton [3] and Pope [4], and in ventilation practice. After counting all the losses, it was decided to use a one horsepower variable speed D. C. motor for this wind tunnel. The motor is mounted outside. Belt driven system is used to drive a six blade, 24 in. diameter propeller fan. Both motor and fan are commercially made.

One transition section on each side of the fan is used. These two sections connect the circular fan section to the square cross-section of a diffuser and a corner section, respectively. Straightener vanes are installed at downstream side of the fan. The motor, control switch, driving belts, fan, and two transition sections are shown in Figure 4.

3. Calibration

The variation of the dynamic pressure, $q = \rho v^2/2$, were measured across a cross-section at six inches downstream from the inlet of the testing section by means of a pitot-static tube. The local velocities may

then be obtained from

$$v = \sqrt{\frac{2q}{\rho}} \tag{1}$$

and normalized by the velocities obtained from the center region. Velocity variation in percentage for the cross-section is shown in Figure 5. The center region of 188 square inches has less than 0.5% variation from the mean velocity. Because of the flexibility of plexiglass, two sidewalls and the ceiling have thicker layers of velocity variation between 0.5 to 4%, whereas on the plywood floor the boundary layer is 1/2 in.

4. Demonstration of Wind Flow Patterns Around a Building Model

As mentioned earlier, a wind loading study on a full-scale building was carried out by Marshall and Hsi [1]. It was, therefore, particularly interesting to know the flow characteristics around the building under investigation. Flow phenomena, such as vortex formation, strong separation, reattachment, and wakes have significant bearings on local wind loadings. Most flow separations are known to occur along the sharp edges and corners of windward building walls. On the other hand, the occurrence and location of the other flow phenomena on a building are not obvious. The model study would thus be most helpful to spot the locations where elaborate measurements on a full-scale building are necessary.

The building model under investigation was scaled linerly down from a rectangular prototype having 47 ft. in height and 367 ft. in width for the wide wall and 103 ft. for the narrow wall. The modeling scale is 1:400 and the model is made of wood. Tufts are used for demonstrating flow phenomena around the model. The tuft is made of wax string and glued to a small glass bead. With another glass bead acting as a bearing, these

two beads are pinned loosely down on the model surface. The tuft will thus follow the streamline and show the flow characteristics near the model surface at that location. The arrangement of tufts on the model surface was based upon the possible occurrence of important flow phenomena.

The following will show the presence of a near two-dimensional flow over a low building normal to the wind, the flow separation and reattachment, and vortex formation via visualization technique. The modeling criteria also are discussed.

4.1 Some Considerations on Building Modeling

For rigid building models geometrical, kinematic and dynamic similarity are of main concern. Geometrical similarity is achieved by constructing an undistorted model linearly scaled down from the prototype. The scaling factor is chosen according to the size of the wind tunnel cross-section. Large flow blockage would include severe deviation to the true result. Thus, it is a good practice to keep the tunnel blockage within five percent, and in turn the model scaling factor can be determined. It is, however, desirable to have the model scale from 1:100 to 1:500.

Kinematic similarity includes simulating mean velocity distribution, ratio of boundary-layer thickness to height of the building, and turbulence field. With adequate upstream roughness, surrounding structures and proper approaching wind profile, the kinematic similarity can be closely achieved in a wind tunnel. In this report, the model was investigated in an approximately uniform flow field with relatively thin boundary layer. The flow patterns around the model would be qualitatively similar to the closely modified case.

Dynamic similarity for a neutral flow is expressed in terms of Ross-

by and Reynolds number. For building model study, the Rossby number is relatively insignificant, if the concerned flow field is rather close to the ground. Coriolis force effect is not important in this case. The equality of Reynolds number between model and prototype is observed for aerodynamic studies. Different ranges of Reynolds number show distinct characteristics in the wake region on a bluff body. However, the building model with sharp corners and vertical edges can be treated as independent of the Reynolds number. There is no firm theory to explain this conventionally adopted approach, but it is evident from experimental results. The model studied in this report is treated as independent of the Reynolds number.

4.2 Near Two-Dimensional Flow Over a Low Rise Building

The building model under investigation has the height-width ratio about 1 to 8, and the building may be classified as a low-rise structure. When the approach wind is normal to its wide wall, the flow near the center portion of the building would approximately be two-dimensional. A drawing is furnished in Figure 6 indicating the flow pattern in that region. A standing eddy can be seen in front of its windward wall. This is due to the fact that the pressure near the top of the windward wall is larger than at the bottom. Consequently, a region of reversed flow and a forward flow separation occur near ground level. The size of this reversed flow zone is varied with the height-width ratio of the building and the velocity profile of the approaching wind [5]. Large pressure and velocity fluctuations can be found on the windward wall as a result of vorticity amplification in the flow stagnation zone and of no fixed spearation by geometry. The mean pressure is usually much larger at upper levels than at lower levels. For a high-rise building the mean pressure may

have a sevenfold difference along the windward wall. The fluctuating and peak pressure exhibit an opposite trend. They are larger at the lower windward wall. Near structure base fluctuation pressure that amount to four times the mean pressure is found [6].

Relevant pressure coefficients are defined as follows. Let q be the dynamic pressure of free-stream, the local mean pressure coefficient may be written as [6],

$$C_p = \overline{\Delta p}/q \tag{2}$$

where $\overline{\Delta p}$ is the mean pressure. In the same fashion, the local fluctuating pressure coefficient and the local instantaneous peak pressure coefficient are defined as

$$(C_p)_f = Prms/q \tag{3}$$

and

$$(C_p)_{max} = p'_{max}/q \tag{4}$$

where p_{rms} denotes the root-mean-square value, i.e., $\sqrt{\overline{p'^2}}$ and p'_{max} is half of instantaneous maximum peak-to-peak pressure fluctuations. These defined coefficients will be used late in this report. Figure 7 shows that tufts of top row on the windward wall of the model are all pointing upward, whereas on the bottom row, pointing downward with unstable flow fluctuations present. This clearly demonstrates the existence of a forward standing eddy and turbulent nature of the reverse flow zone. On the other hand, separation is developed along the sharp leading edge of the flat roof top and a reverse flow is occurred close to roof surface see Figure 6 and 8. This boundary layer is highly turbulent and generates large negative pressure on the roof. Maximum negative pressures can be found along the leading edges, and it may be the major reason for roof

damage.

The characteristics of the wake region close to leeward wall is uncertain. However, the main features in that region are these: negligibly small wind velocity in comparison with mean flow and highly unstable and turbulent flow. This complex flow phenomenenon is illustrated in Figure 8. Random flow pattern can be found among these four tufts on the leeside of the model, although tufts are arranged close to each other. On the leeward wall the mean pressure is negative and has less variation than on the windward wall. However, the fluctuating and peak pressure can be the same order of magnitude as on the windward wall.

4.3 Flow Separation and Reattachment

Local wind-pressure fluctuations from flow separation and reattachment when combined with pressure due to the mean wind, can produce high instantaneous loading on outer skin elements of a building. Many failures of window glass and cladding panels indicate that adequate evaluation of local wind-pressure loadings is important.

For a building with sharp edges or corners, flow separation will invariably occur. In some cases, the separation streamline may contact the building surface some distance downstream at a reattachment point. The location of the separation point is fixed while the location of a reattachment is unstable and moves from point to point in a region of limited extent, called reattachment zone [7]. These flow characteristics are shown in Figure 9. As the model is set at an angle with respect to the approach wind, flow separation occurs at its sharp windward corners, and reattachment takes place at a distance downstream on its two side walls. After flow separation, the reattachment, however, does not necessarily occur

even if there is a relatively long and solid boundary downstream. As shown in Figure 10, the narrow wall of the model is set normal to the flow, only separation prevails and no reattachment exists along its side wall. On the other hand, the reattachment is clearly seen on its roof. The first row of tufts near the roof leading edge is pointing against the oncoming wind while the rest of the tufts are following the mean flow direction. In this case, the reattachment zone is between the first row and second row of tufts. By varying the model orientation with respect to wind direction, the flow reattachment does occur at about one third of side wall length downstream from the separation edge along its side wall, as shown in Figure 11. The flow phenomena over the roof is similar to these shown in Figure 10.

Flow separation and reattachment are major features concerned with wind loading on buildings. The separation-induced pressure fluctuations are sufficiently intense to require special care in the design of windows and cladding panels. In the zone of reattachment, for instance, the surface pressure is highly variable and pulsations of large magnitude may occur. In addition to these mean and fluctuating pressure, the repeating nature of pressure pulsation may be the explanation for fatigue failure of the outer skin elements. These local wind loads information due to the intensities of separation and reattachment is furnished in the following.

The result from the model study of New York World Trade Center and Bank of America World Headquarters Building, by Cermak [7], reveals important information concerning the reattachment zone. The root-mean-square pressure fluctuations with a re-entrant corner amounts to $(C_p)_f$ = 0.45. For a square cross-section without re-entrant corners, reattach-

ment on a smooth wall will give a maximum rms of the pressure fluctuations of about $(C_p)_f = 0.25$. The maximum instantaneous pressure fluctuations for both cases was found to be four times the rms value. The result is consistent with the conclusion of Davenport [8]. Cermak [7] also pointed out that the maximum value of pressure fluctuation occurs in a region with $\frac{\partial C_p}{\partial X} > 0$, where C_p is the mean pressure coefficient and X is the distance along the wall. This shows that reattachment occurs in a region in which some of the kinetic energy in the mean flow near the separation streamline is recovered as an increase in potential energy. The location where the largest pressure fluctuation will occur can be determined from the model. He found from the study of the aforementioned two models that at corner at the separation point the mean pressure coefficient amounts to -2, and the $(C_p)_{max}$, ± 1.6. An instantaneous pressure at separation point resulting from the mean wind and the separation induced pressure fluctuation can attain the total pressure coefficient of -3.6.

4.4 Vortex Formation on a Building Model

Vortex flow around a building are not easily observed and described. In general, these flows are happened along edges and corners of a structure where discontinuities of flow field occur. Vorticies dissipate rather quickly into a mean flow field. However, steady edge vortices can be generated along the edges of roofs and corners due to building geometry and wind direction. In this report, the tufts visualization technique demonstrated clearly the vortices on the model surface. Figure 12 and 13 show steady vortices exist on the surfaces of the model. There are four steady edge vortices on the roof surface and one vortex at the leading upper corner of the narrow wall, while the model is set at 6.5 degrees

with respect to the wind direction, as illustrated in Figure 12. When the model is set at -12 degrees, four vortices appear on the narrow wall, as shown in Figure 12. This may indicate the existance of conical vortices sweeping across the narrow wall. The rotating direction of these vortices and vortex flow of Figure 13 is depicted in a schematic diagram in Figure 14.

Vortex flows developed by the combination of building shape and wind direction can cause strong pressure pulsations of various frequencies and magnitude. In certain cases, these pressure pulsation may become intense enough to result in breaking windows or cause fatigue failure in cladding panels. Ostrowski, et. al [9] found that vortices can attach themselves to the peaks of saw-tooth geometry of walls and roofs and generates strong pressure pulsations of the structure. Marshall and Cermak [10] gave indication about a particular structure that the average intensities of the pressure pulsation are on the order of 1/2 the dynamic pressure, and the maximum peaks on the order of 1.5 times the dynamic pressure.

5. Conclusions

(1) A small and simple wind tunnel is constructed at reasonably low cost of $3200 and in a confined space of a typical office room. This tunnel gives flow performance adequate for qualitative building model studies. Architecture firms, consulting engineers, colleges and universities will find the feature of this tunnel most attractive to their professions.

(2) A tuft visualization technique is successfully used to demonstrate flow patterns, flow separation and reattachment, vortices, and wakes around a small rigid building model. Tufts and the model reveals

most significant characteristics of flow-building interaction, and points out the areas of potential danger on the building outer skin elements.

(3) The significance of flow separation and reattachment, vortices, and wakes on local wind loads on buildings are described via existing information. Their influence would be the major concern for designing a building to stand high winds.

6. Acknowledgements

The author is indebted to Mr. W. G. Spangenberg, Aerodynamics Section, NBS for many valuable comments and suggestions on design of this wind tunnel.

Mr. F. Rankin did excellent work on the construction of the wind tunnel and shares credit for its good flow performance.

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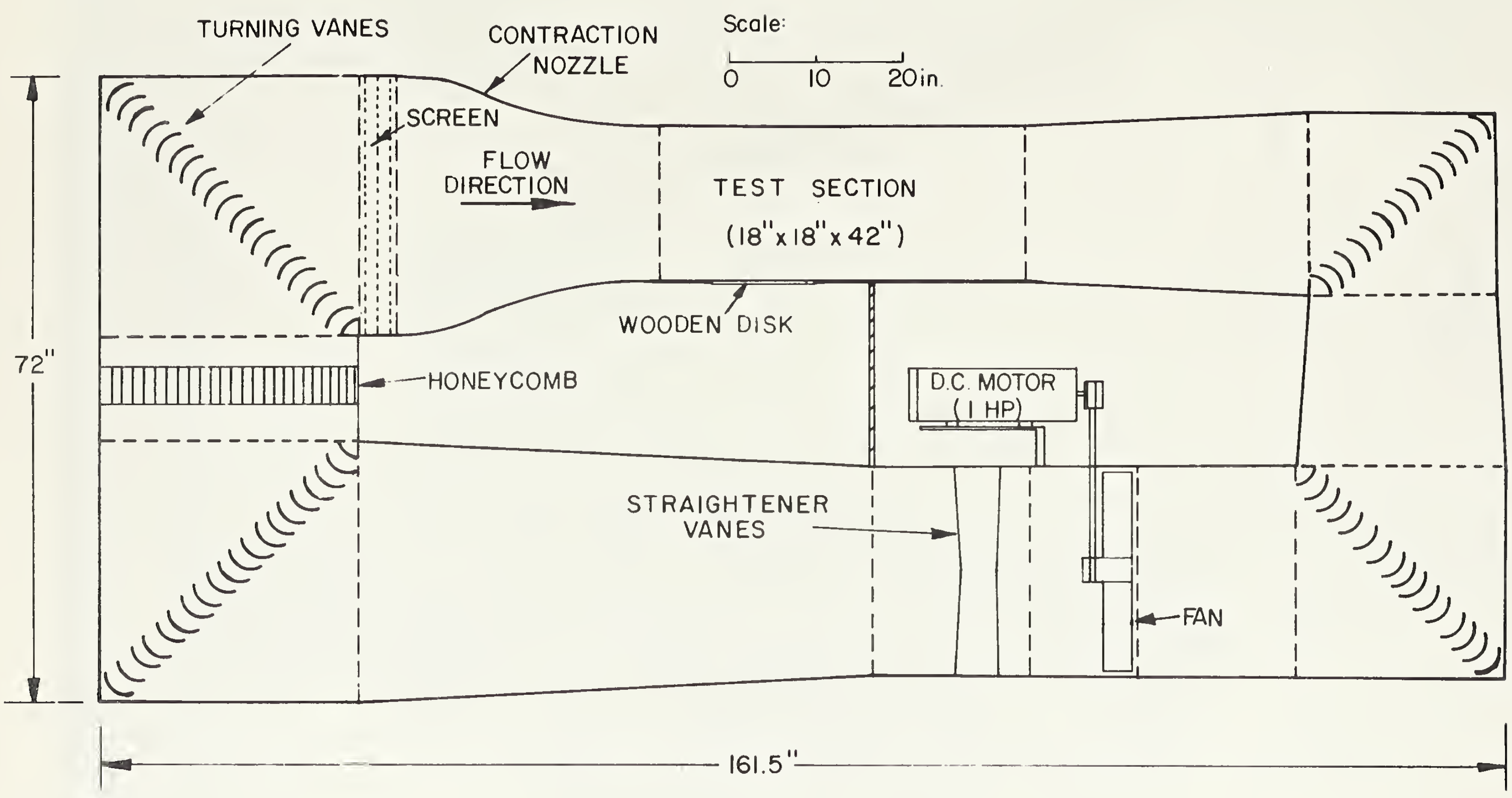

Figure 1 Structures Section low speed wind tunnel.

Figure 2 Photograph of low speed wind tunnel.

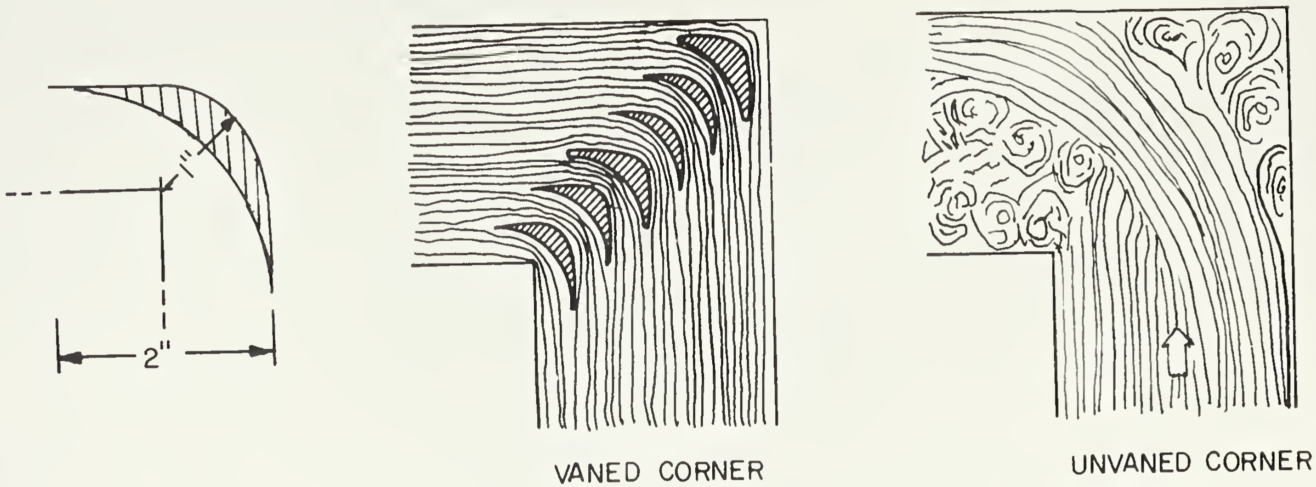

Figure 3   Wind tunnel corner and turning vane.

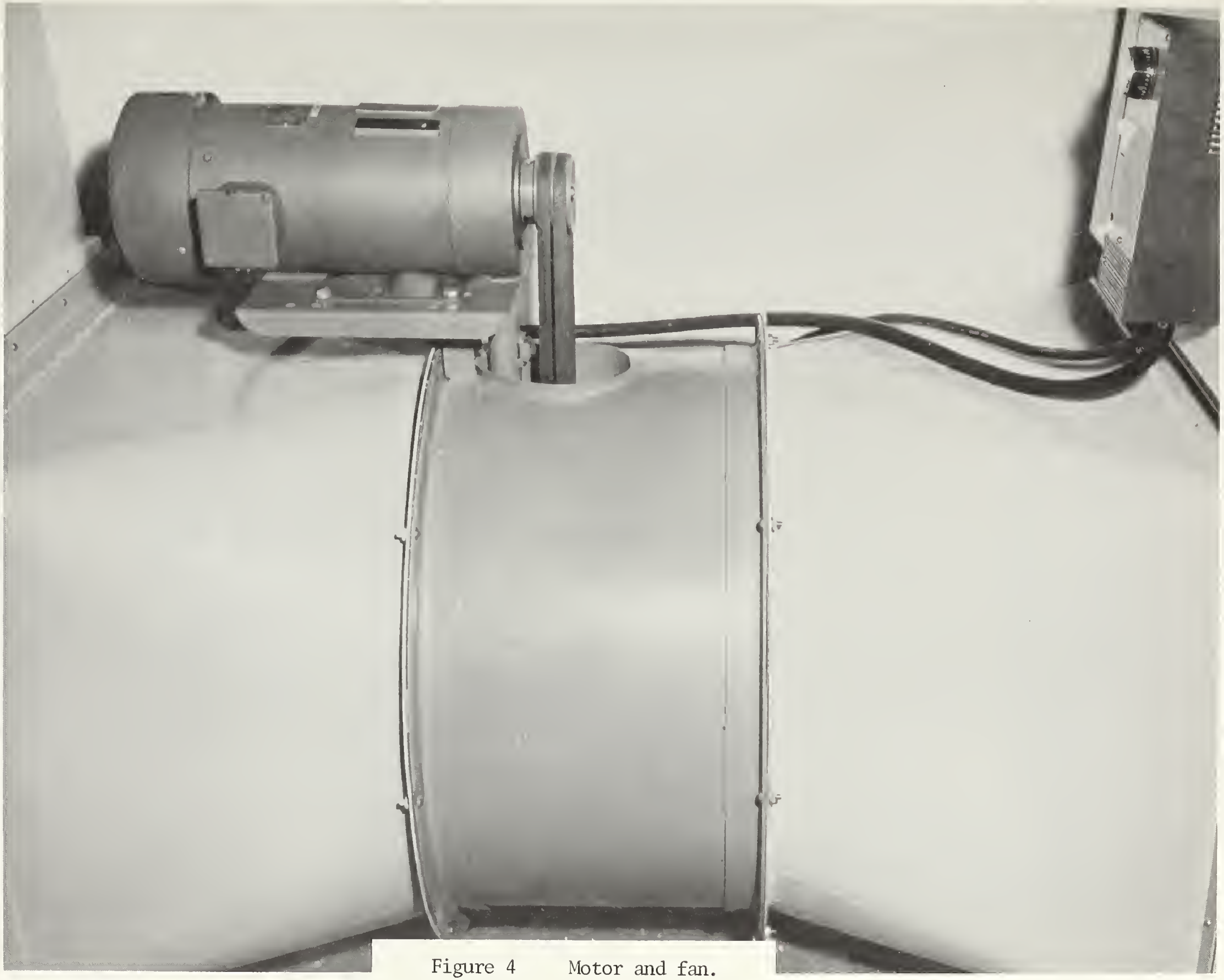

Figure 4 Motor and fan.

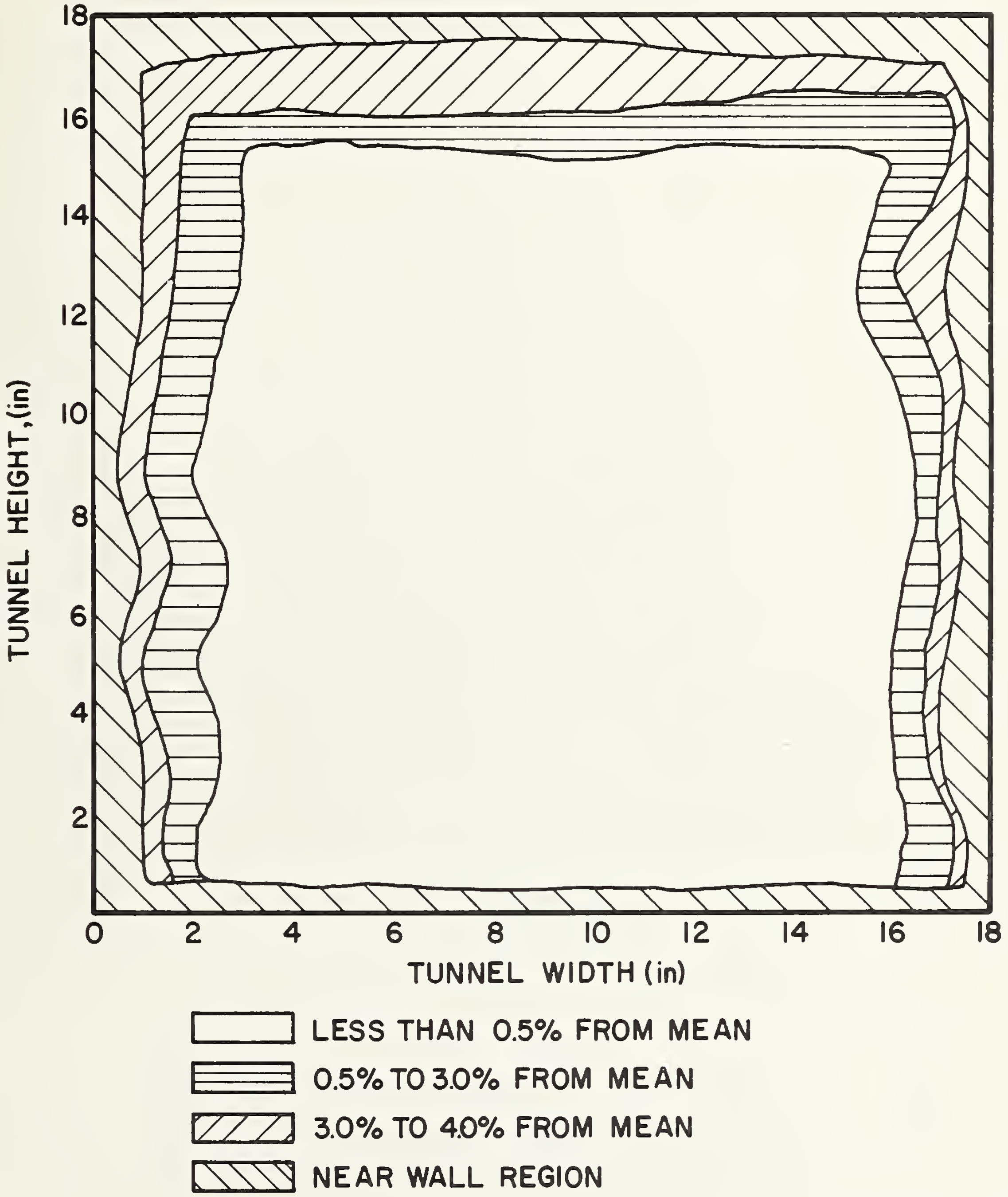

Figure 5 Velocity distribution at six inches downstream from inlet, view from upstream.

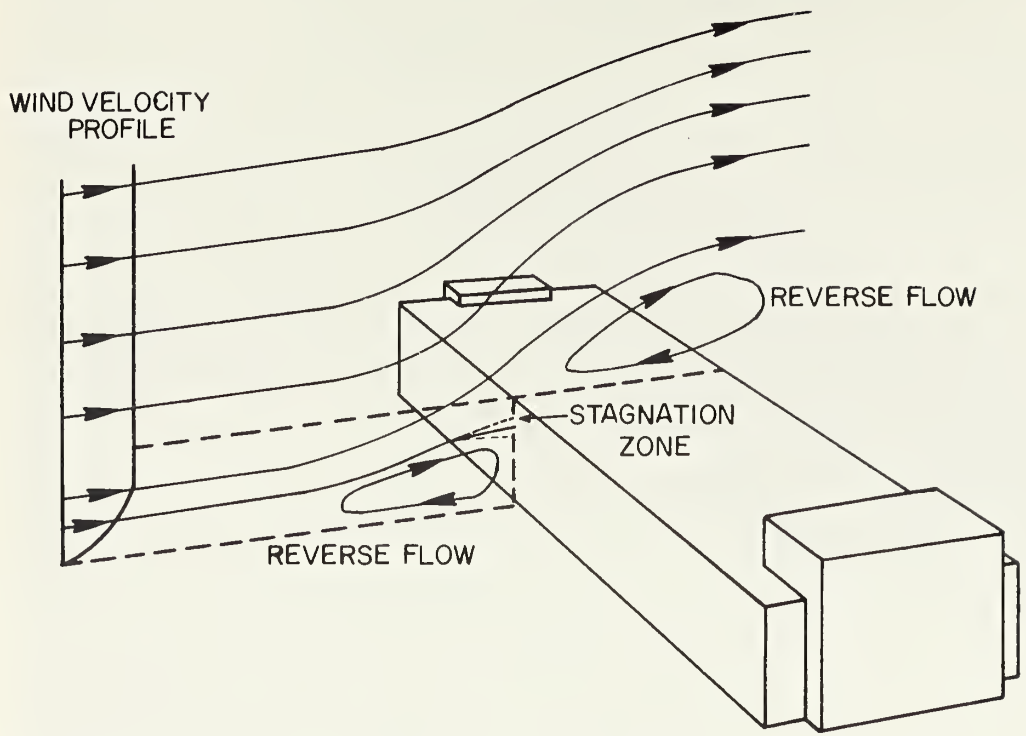

Figure 6 Two dimensional flow pattern over roof and near windward wall.

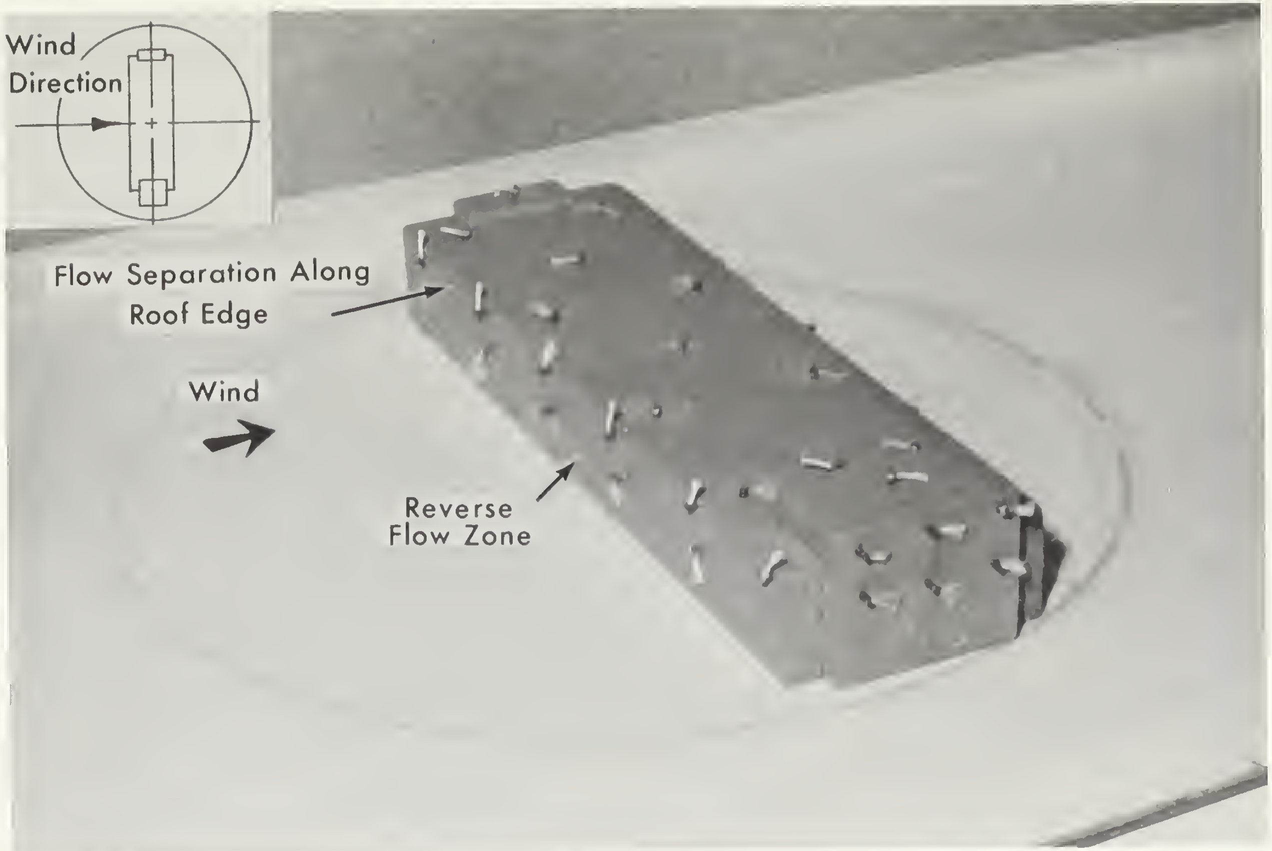

Figure 7 separation along roof edge.

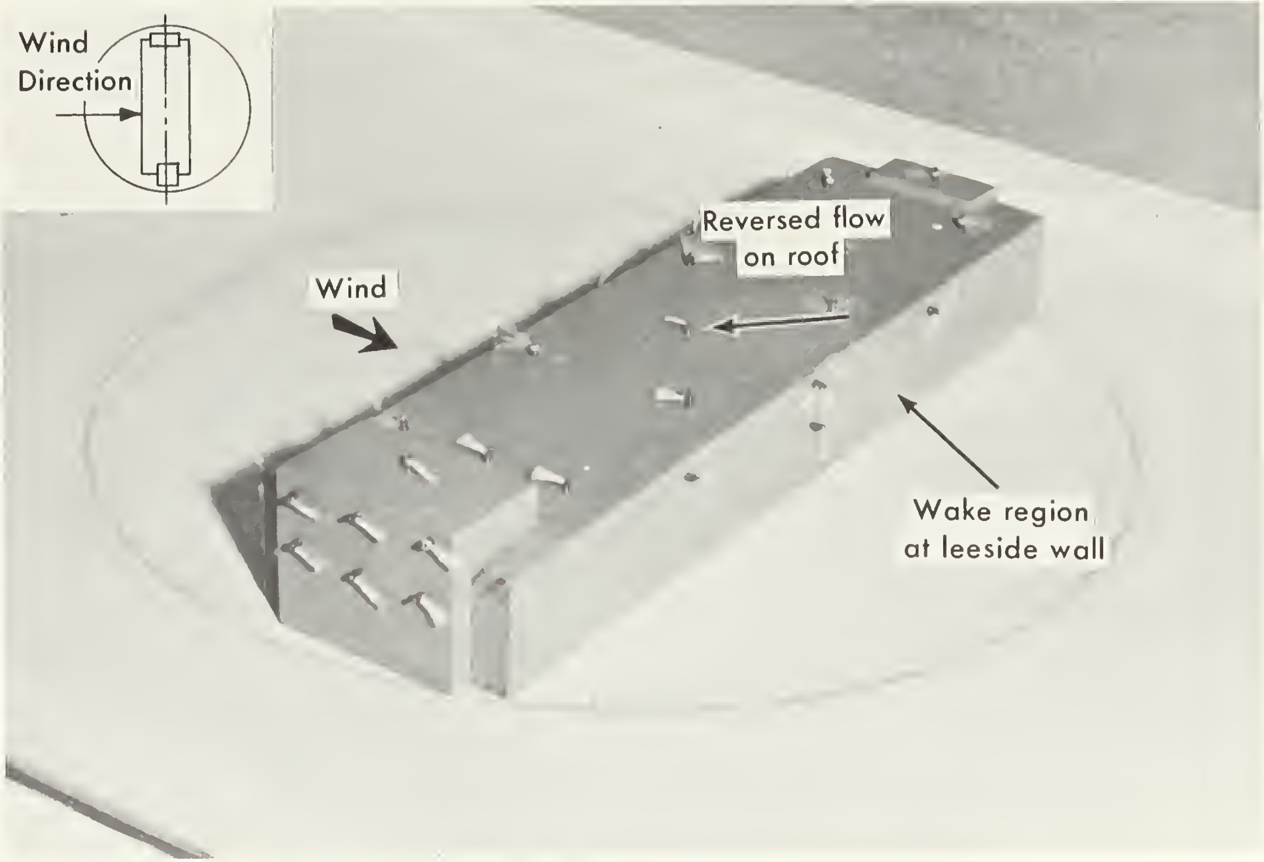

Figure 8 Reversed flow on roof and wake region at leeside wall.

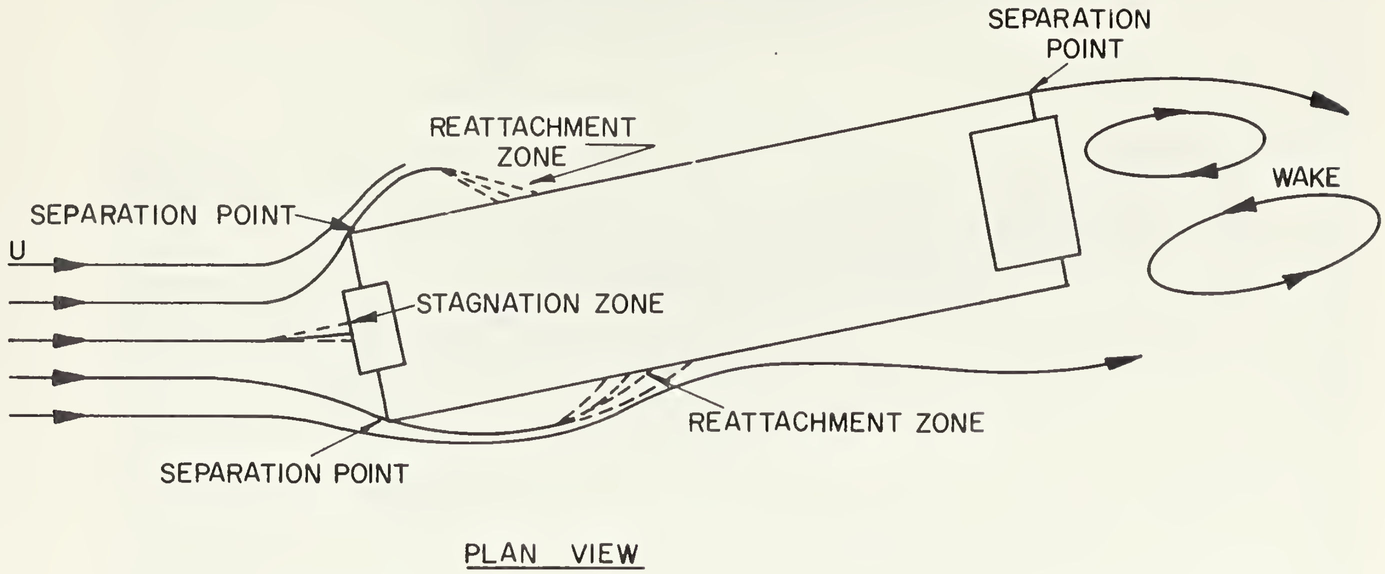

Figure 9 Features of flow separation and reattachment around a building model.

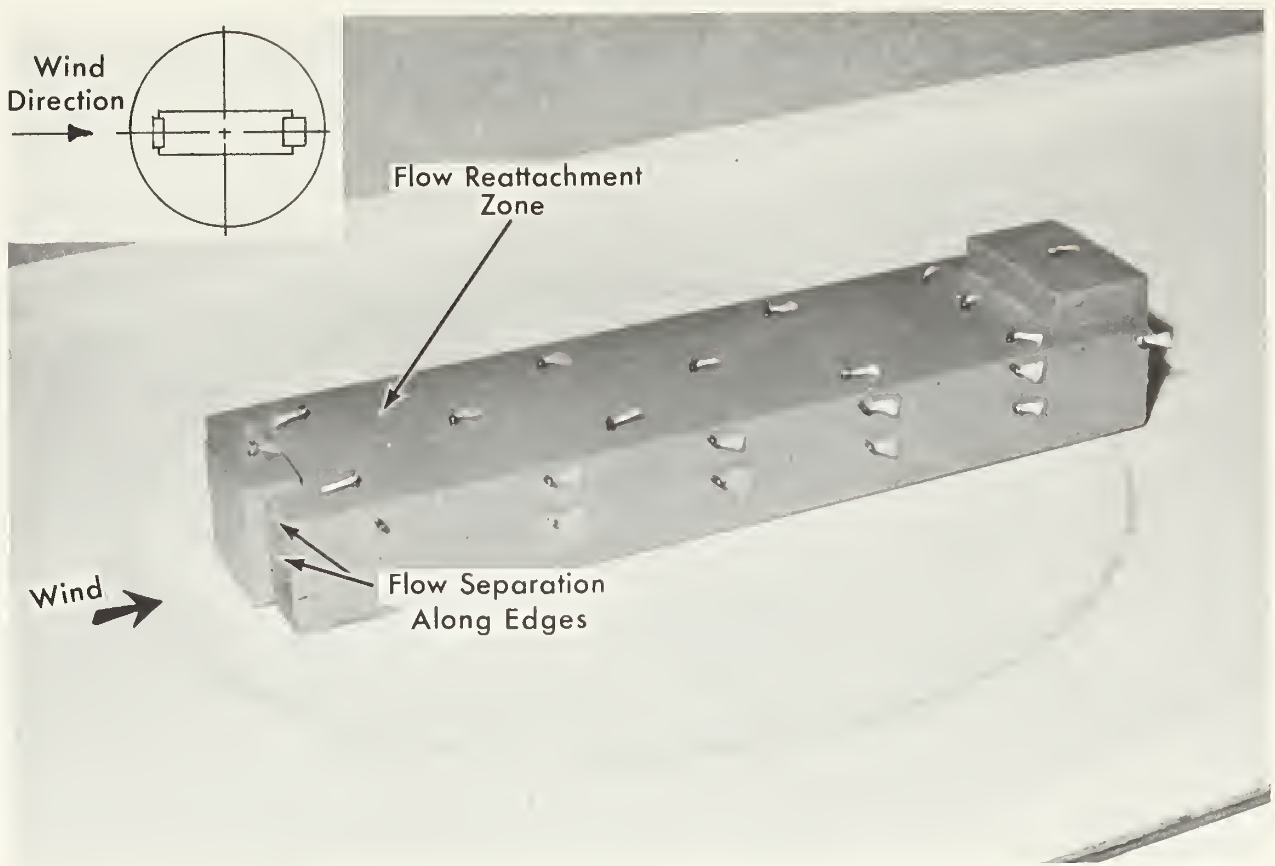

Figure 10   Flow reattachment of roof and separation along edges.

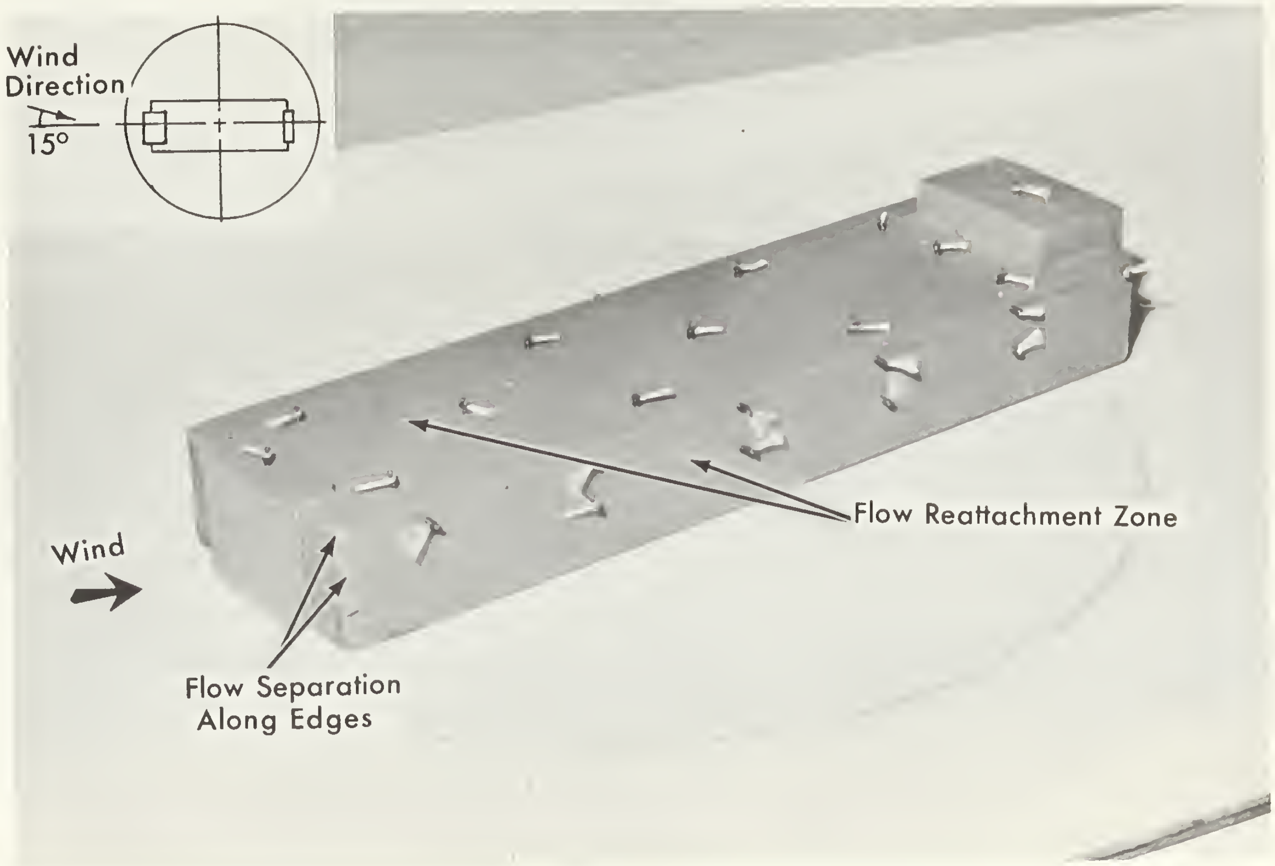

Figure 11 Flow separation and reattachment on roof and side wall.

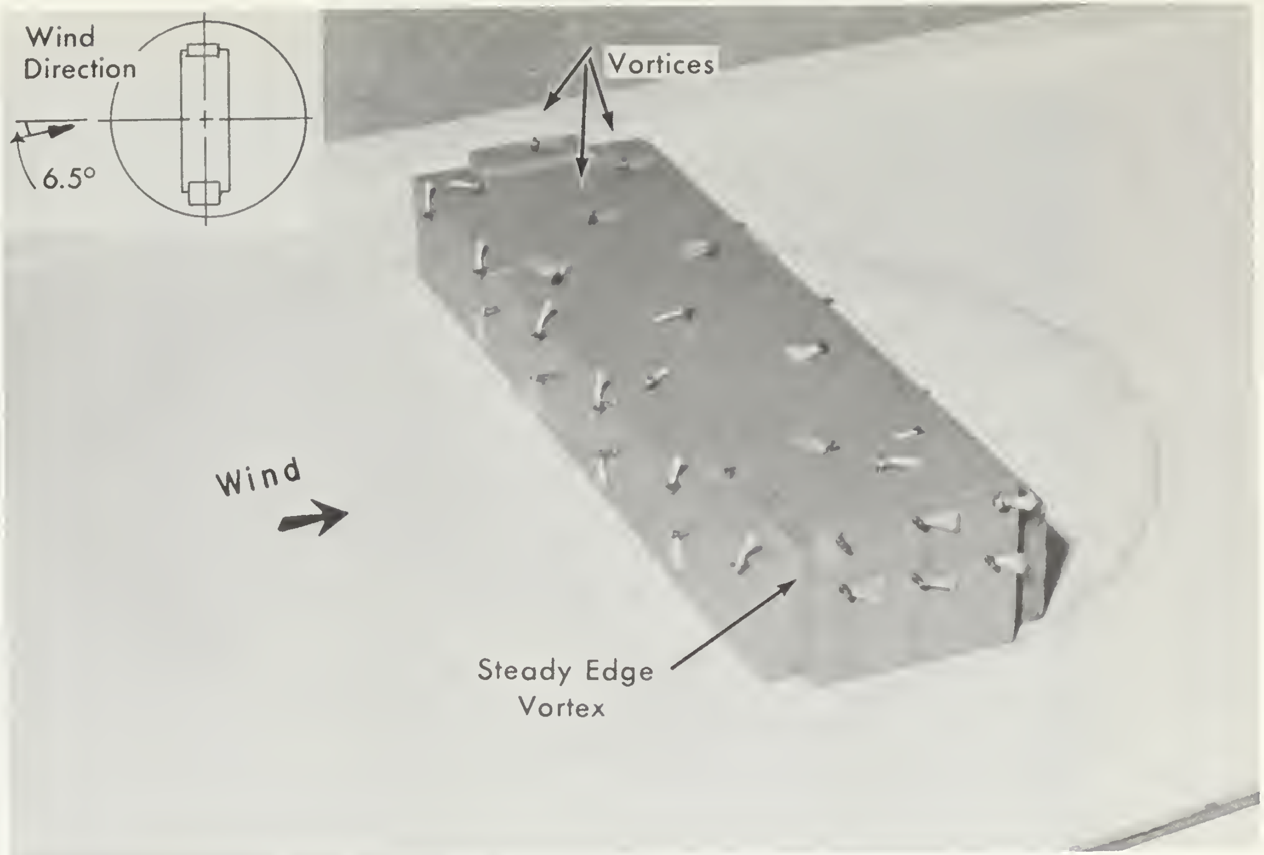

Figure 12 Steady edge vortex at upper leading corner of narrow wall and vortices on roof.

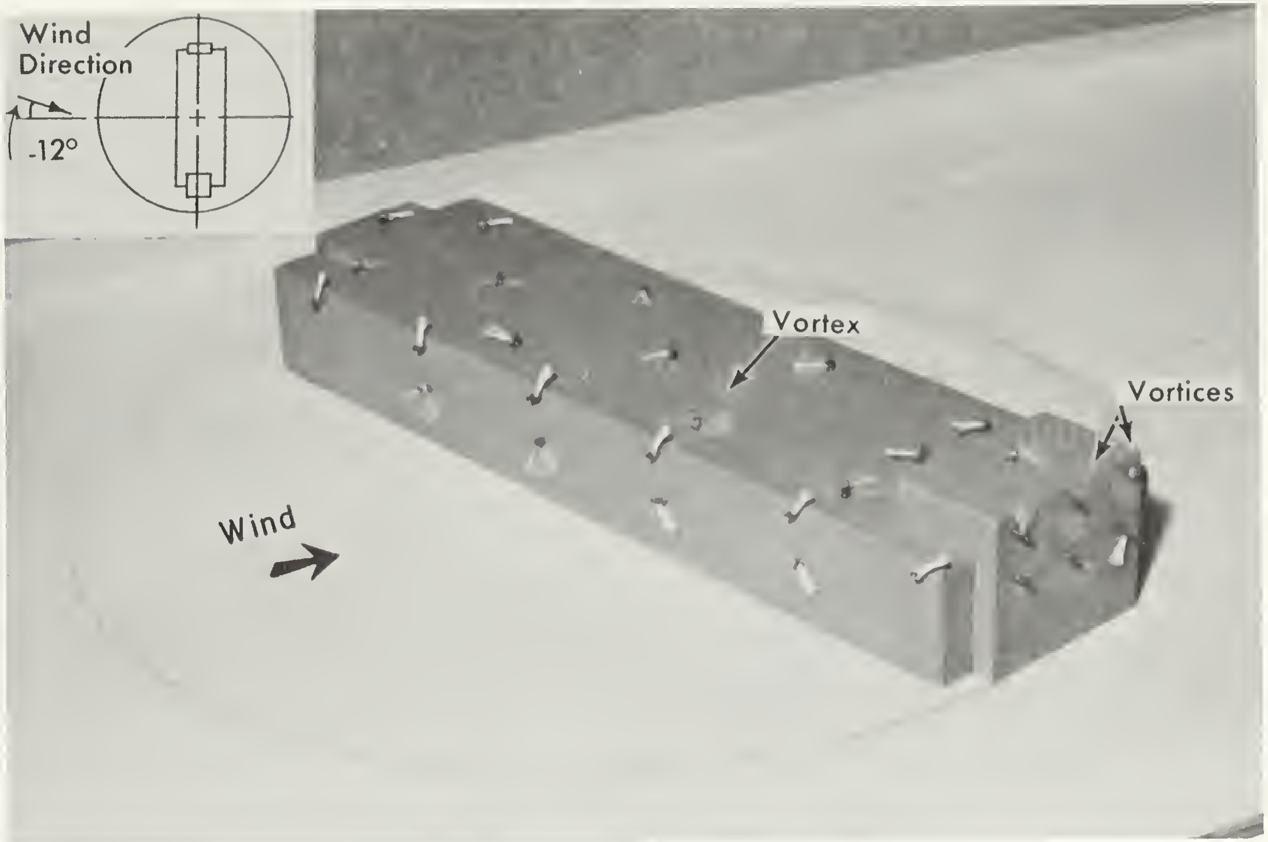

Figure 13   One vortex on roof and vortices on narrow wall.

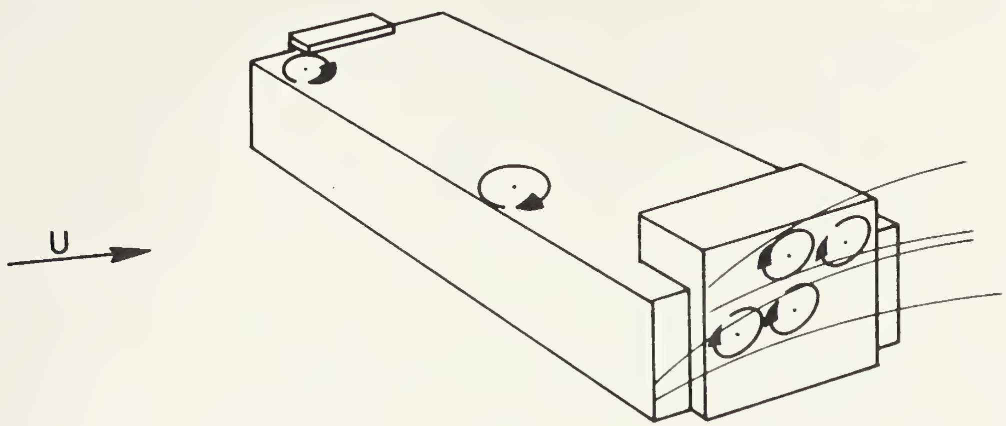

Figure 14 Vortex formation on building model.

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