Wind-Tunnel Measurements of Flow Fields in the Vicinity of Buildings

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WIND-TUNNEL MEASUREMENTS OF FLOW FIELDS IN THE VICINITY OF BUILDINGS

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1. INTRODUCTION

In order to develop physically realistic models that predict the behavior of pollutants released in the vicinity of buildings, an understanding of the flow field is essential. The main features of such flow fields around isolated block-shaped buildings are reasonably well understood (Hosker, 1984). Separation of the flow generally occurs at the leading edges of the roofs and sides of the buildings and these separated layers move into the surrounding fluid. If the building is sufficiently long, these separated layers may reattach onto the surface, so that separation will occur again at the downwind edges of the roof and sides. Whether the building is long or short, these separated layers will eventually curve inward toward the wake axis, forming a rather imprecisely defined region called a "cavity". It is bounded upwind and above by the separation streamline emanating from the roof edge, and downwind by a reattachment streamline. Unlike two-dimensional flows, the separation streamline is not the same as the reattachment streamline (see Hunt *et al*, 1978, as well as later discussion). The "cavity" is also bounded laterally by the streamlines emanating from the corners. Within this roughly ellipsoidal-shape cavity, the flow is of exceptionally high turbulence intensity and small mean velocity, and frequently reverses direction.

Because of the shear in the approaching atmospheric boundary layer, a stagnation point will appear well-above ground on the upstream building face, with upward flow on the surface above the point and downward flow below it. An associated vortex will thus be formed at the upwind base of the building; it is forced around the sides of the structure and trails off downwind. Because of its shape as viewed from above, it is frequently referred to as a horseshoe vortex.

Some of the gross features of the flow fields, such as the length of the cavity, have been parameterized, primarily from flow visualization studies (see, for example, Hosker, 1984). With the notable exceptions of works by Castro and Robins (1977) and Davies *et al* (1980), few detailed flow-field measurements have been made, primarily because of the difficulty in dealing

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with the reversing flow fields in the wakes. Much remains to be understood and quantified. The present experiments take advantage of symmetry to examine the flow fields in vertical centerplanes as the building dimensions are systematically varied. Although both mean velocity and turbulent fluctuations were measured during these experiments, we concentrate in the present report on the mean flow fields; we show how, with the wind perpendicular to a building face, the mean streamline patterns change as the length, width, and height of a building are systematically changed. A cubical building is also rotated 45° to examine changes in the streamline pattern.

2. EXPERIMENTAL DETAILS

The experiments were conducted in the EPA Meteorological Wind Tunnel (Snyder, 1979). The "buildings" were rectangular-shaped blocks which were immersed in a simulated atmospheric boundary layer that was generated using the Irwin (1981) system of "spires" and roughness on the floor downwind. This combination produced a 2-m deep boundary layer with a roughness length of 1 mm. The standard of reference was a cubical building with dimensions of 200 mm on each side. Four series of measurements were made. In the first, the crosswind dimension of the building was increased to 2, 4 and 10 times that of the cube. In the second series, the flow fields were measured behind buildings with along-wind dimensions of 0.015, 0.5, 1, 2 and 4 times that of the cube. In the third series, the height of the building was increased to 2 and 3 times that of the cube. Finally, the cube was rotated 45°.

A pulsed-wire anemometer (PWA) was used for the velocity measurements. This instrument is superior to the hot-wire anemometer for use in flows of very high turbulence intensities and, especially, in reversing flows (Bradbury and Castro, 1971). It is less suited for low intensity flows, especially for measuring components perpendicular to the mean flow vector. The basic principle of operation of the PWA is that of the measurement of the transit time of a heat pulse from a central wire to either of two sensor wires, one located upstream, the other downstream, of the central pulsed wire.

The PWA probe was oriented to measure the velocity components (one at a time) in the longitudinal and vertical directions. Measurements were made at approximately 300 points in the vertical centerplane both upwind and downwind of the buildings for each case.

3. RESULTS

Mean velocity and turbulence intensity profiles of the simulated atmospheric boundary layer in the vicinity of the model buildings (but in their absence) were measured with hot-wire anemometry and are shown in Figure 1. The boundary layer was approximately 1.8 m deep and may be characterized reasonably well by a power-law profile with an exponent of 0.16. The roughness length z_o and friction velocity u_*/U_R were found to be 1 mm and 0.05, respectively. At an assumed scale ratio of 200:1, these parameters correspond to a full-scale boundary layer typical of rural terrain with shrubs and small trees.

Turbulence intensity profiles are also shown in Figure 1, where they are compared with bounds suggested by ESDU (1972, 1974) with full-scale roughness lengths between 5 and 50 cm. Our data, corresponding to a full-scale roughness length of 20 cm, generally fit within the bounds suggested by ESDU.

Figure 2 shows the mean streamline patterns deduced from the mean-velocity measurements in the centerplane for the first series of experiments, where the only parameter varied was the crosswind width (W) of the building. These streamlines were generated using a commercially available program TECPLOT, where a predictor-corrector algorithm is used to move a point in small steps in the direction of the local velocity field. (We have assumed that the crosswind component of mean velocity is zero on this plane of symmetry.)

The main features of upstream stagnation point, separation and reattachment streamlines, and "cavity" are immediately apparent in Figure 2. The cavity size obviously increases as the crosswind width of the building increases, but other aspects of the flow field change markedly also. The location of the stagnation point on the upwind face of the building appears to move only slightly upwards from its cube height of approximately 2H/3, but the *far upstream* elevation of the stagnation streamline changes continuously from about 2H/3 for the cube to essentially ground level for the building with crosswind width of 10H. The streamlines upstream of the buildings thus slope much more prominently upwards as the building width is increased. The horseshoe vortex is barely perceptible upwind of the cube, but grows in size as the crosswind width of the building is increased. At W = 10H, its diameter appears to be about H/2.

The implications of the above flow fields on plume behavior should be obvious. Low plumes from sources located upwind of rather narrow buildings are quite likely to impinge directly on the upwind building faces, whereas those from sources located upwind of wider buildings are much more likely to be lifted over the top, with perhaps only the lower edges of the plumes diffusing to the building surface.

That the flow separates from the upwind edge of the roof is apparent in all cases shown in Figure 2. In the case of the cube, this separation streamline clearly reattaches to the roof, as was also evidenced by Castro and Robins (1977). This reattachment is followed immediately by a horizontal separation from the downwind roof edge, and the cavity height appears to be constrained to be the same as the building height. For the wider buildings, however, whereas the initial separation streamline appears to reattach to the roof, a horizontal separation at the downwind roof edge does not exist. Instead, the cavity grows in height and the associated upward velocities on the lee face of the building appear to predominate, with separation of the flow progressing up the lee building face. This is obviously associated with the much stronger vertical velocities in the cases of the wider buildings. The cavity height grows from about H in the case of the cube to about 3H/2 in the case W = 10H.

The length of the cavity (from the lee face of the building to the reattachment point) varies from 1.4H for the cube to 5.6H when W = 10H. These values agree quite well (within about 10%) with Hosker's (1984) equation for the cavity length where reattachment of the flow on the roof was observed. Another point to note for the widest building is the formation of a secondary vortex at the downwind base.

An important point to note here is that these streamline patterns differ qualitatively from those described by Hunt *et al* (1978). They suggest that in the centerplane of a three-dimensional flow, a streamline originates upstream and attaches to the surface downwind (see Figure 3a); streamlines below this one, then, spiral into the node N, so that the flow is laterally *outward* in the y-direction at N. Thus, N is a *separation* point. Our measurements suggest that the flow is laterally *inward* in the y-direction at N, so that it is an *attachment* point. The flow coming onto this centerplane at N, then, spirals outward, forming the attachment point at S on the ground surface (see Figure 3b). The streamline attaching to the surface *does not* originate from upwind, but rather from the node in the centerplane. This topological structure appears more consistent with the streamline patterns presented by Davies *et al* (1980), which were also derived from pulsed-wire measurements for a tall building.

Figure 4 shows how the streamline patterns change as we vary the along-wind length (L) of the building. The upstream patterns appear to be completely independent of L. The cavity height is a maximum (of about 1.4H) when L = 0.015 (square flat plate), since reattachment on the roof obviously cannot occur. When L = H/2, the cavity height is reduced to about 1.15H; for L ≥ H, reattachment occurs on the roof, horizontal separation follows at the downwind roof edge, and the cavity height is constrained to be the same as the building height. Correspondingly, the cavity length (measured from the rear building face) decreases from a value of 2.3H for the flat plate to 1.5H when L = H/2. For L ≥ H, the cavity length is nearly constant with a value near 1.3H. Finally, in the far wake of the short building (L < H), the streamlines are observed to descend quite rapidly, whereas they are more nearly horizontal downwind of the longer buildings.

Figure 5 shows how the streamline patterns change as we vary the building height. The elevation of the stagnation point on the upwind face of the building remains at approximately 2H/3, and the streamlines upstream of about 1.5W are essentially horizontal. According to Corke and Nagib (1976), the height of this stagnation point is rather strongly dependent on the exponent of the power law describing the wind profile, and our value appears to agree quite well with their observations. The streamline pattern above the building is largely independent of building height; in all cases, the flow reattaches to the building roof, then separates again at the downwind edge of the roof. Perhaps surprisingly, the cavity length is independent of the building height, but for a tall building, the distance to reattachment should obviously be more closely linked to the width of the building rather than to its height. The streamline patterns presented here display a free stagnation point (denoted by S), as was also shown by Davies *et al* (1980) through pulsed-wire measurements in the wake of a building with height 6 times its length and width.

The case of flow approaching the cube at 45° is shown in Figure 6. This pattern displays the qualitative features described by Castro and Robins (1977) and others, namely, that the horseshoe vortex is less prominent and that downwash is much stronger in the wake. Although not evident from this centerplane pattern, this flow is dominated by the delta-wing-type vortices generated by the swept-back leading edges.

SUMMARY

A pulsed-wire anemometer was used to measure the flow fields in the vicinity of a variety of rectangular-shaped model buildings immersed in the simulated atmospheric boundary layer of a wind tunnel. The crosswind width, height, and along-wind length of the building were systematically varied, and the longitudinal and vertical components of the velocity fields were measured in the plane of symmetry (centerplane). Measurements were also made with the cubical building rotated to 45°. These measurements were used to deduce the streamline patterns and, hence, to identify and quantify important features of the flow fields.

The location of the stagnation point on the upwind building face was found to be 2H/3, practically independent of the crosswind width or along-wind length of the building. The far-upstream height of the stagnation streamline decreased with an increase in the crosswind width

of the building; when W = 10H, its height was essentially ground level. A horseshoe vortex appeared at the upwind base of the building; it became more prominent as the crosswind building width was increased. The flow always separated at the upwind edge of the roof. It reattached on the roof when $L \geq H$. The "cavity" length and height grew as the crosswind width of the building increased. The cavity length was observed to be independent of building height and, for $L \geq H$, independent of L. Our measurements suggest that the structure of the streamline patterns in the wake is qualitatively different from that described by Hunt *et al* (1978). The flow spirals out of a node located inside the "cavity" and reattaches to the surface.

This data set should prove useful to the mathematician attempting to develop physically realistic models that predict downwash of pollutants released in the vicinity of buildings.

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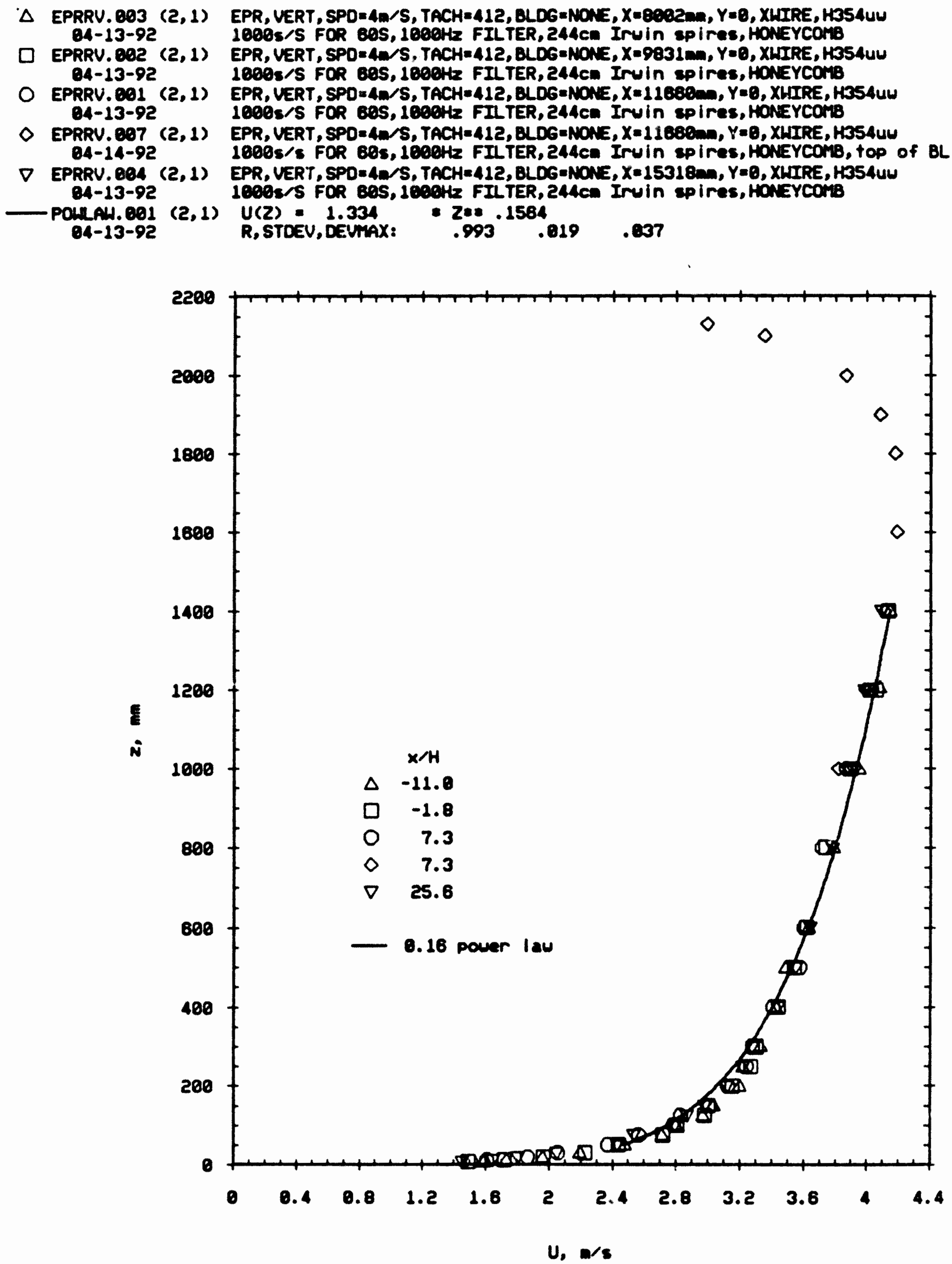
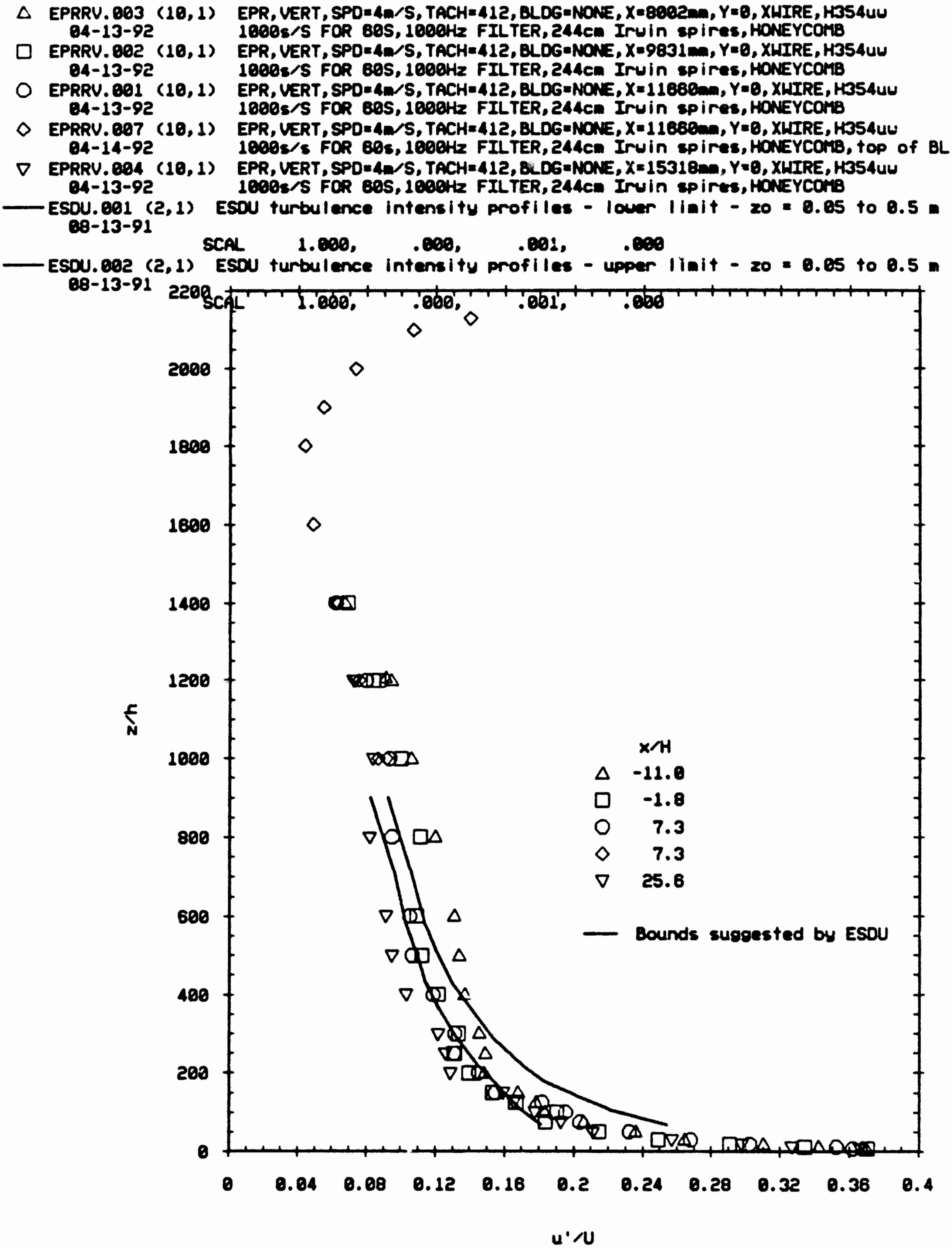


(a) Mean velocity profiles

Figure 1. Simulated atmospheric boundary layer structure.



(b) Longitudinal turbulence intensity profiles

Figure 1. Simulated atmospheric boundary layer structure.

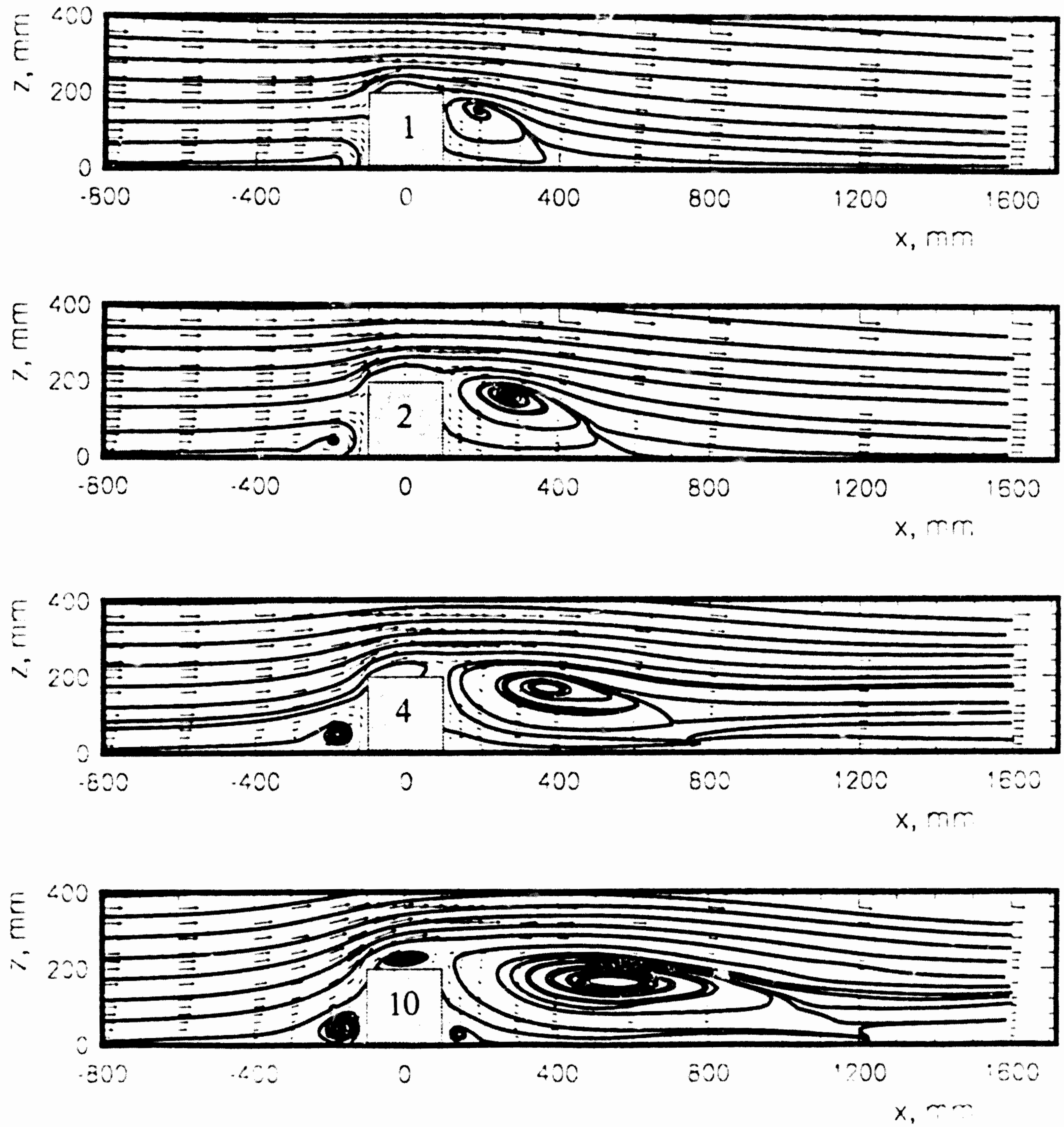


Figure 2. Streamline patterns around buildings of various crosswind widths. Number on building is W/H. L = H.

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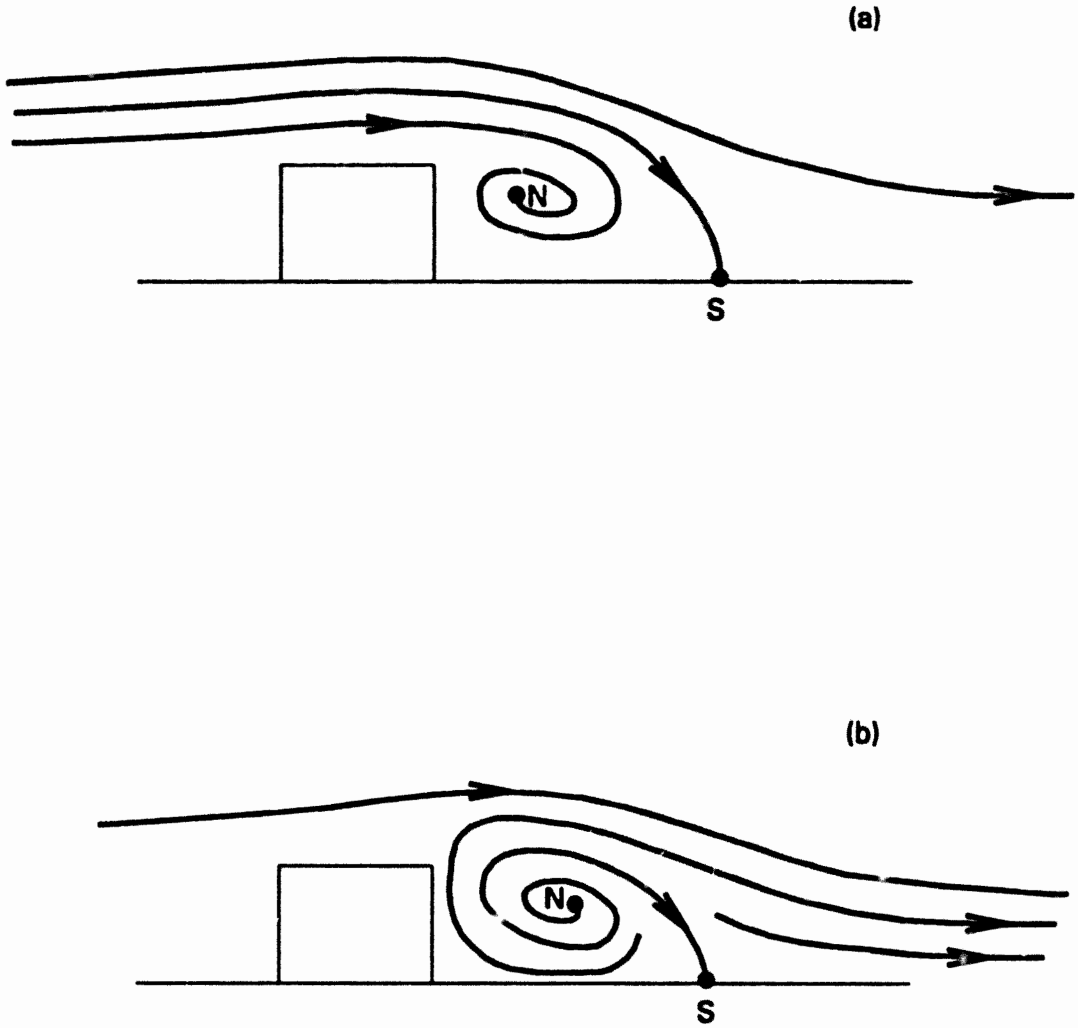

Figure 3. Sketches of basic flow structure as (a) viewed by Hunt et al (1978), where the node N is a separation point, and (b) suggested by current measurements, where the node N is an attachment point.

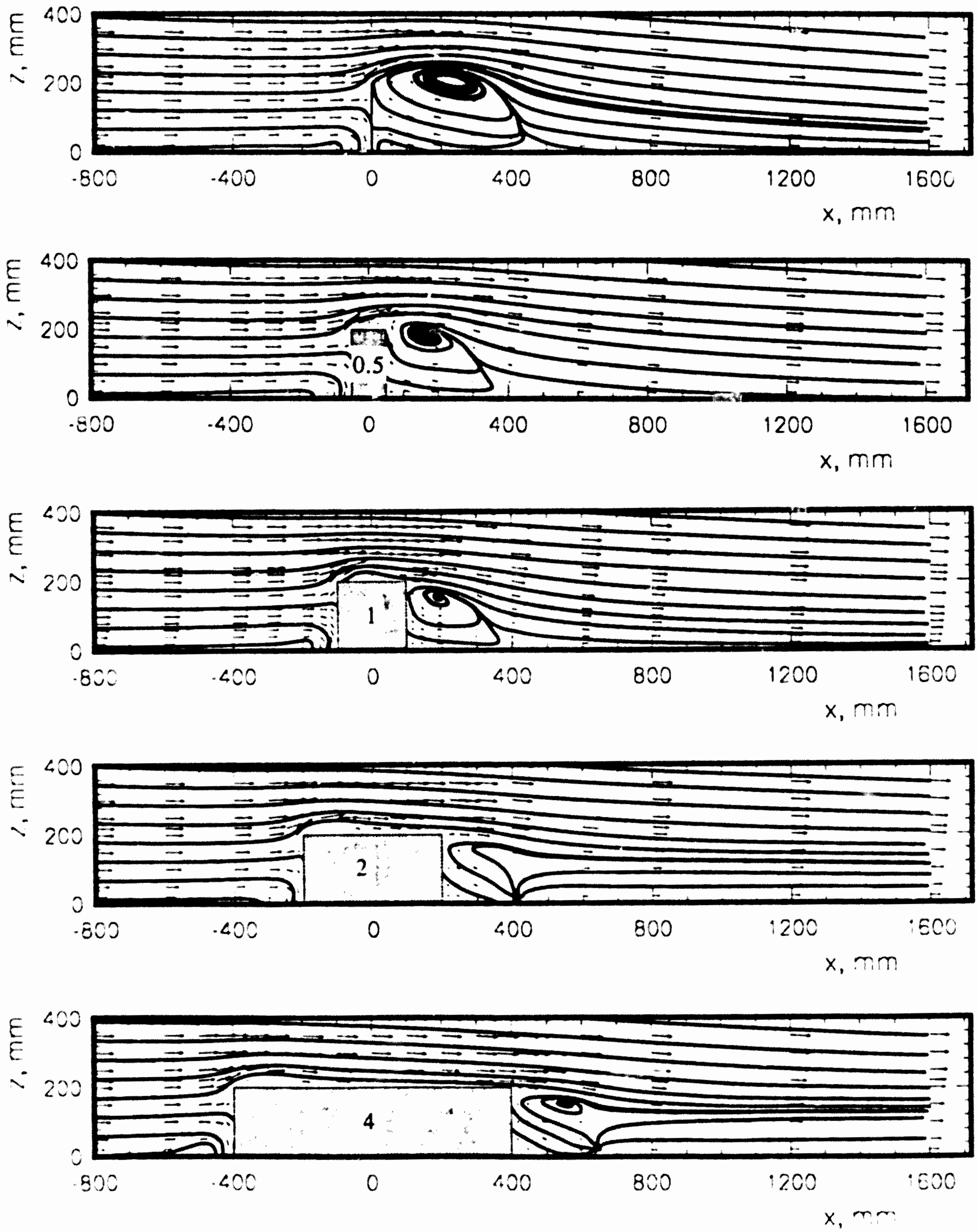

Figure 4. Streamline patterns around buildings of various along-wind lengths. Number on building is L/H. W = H.

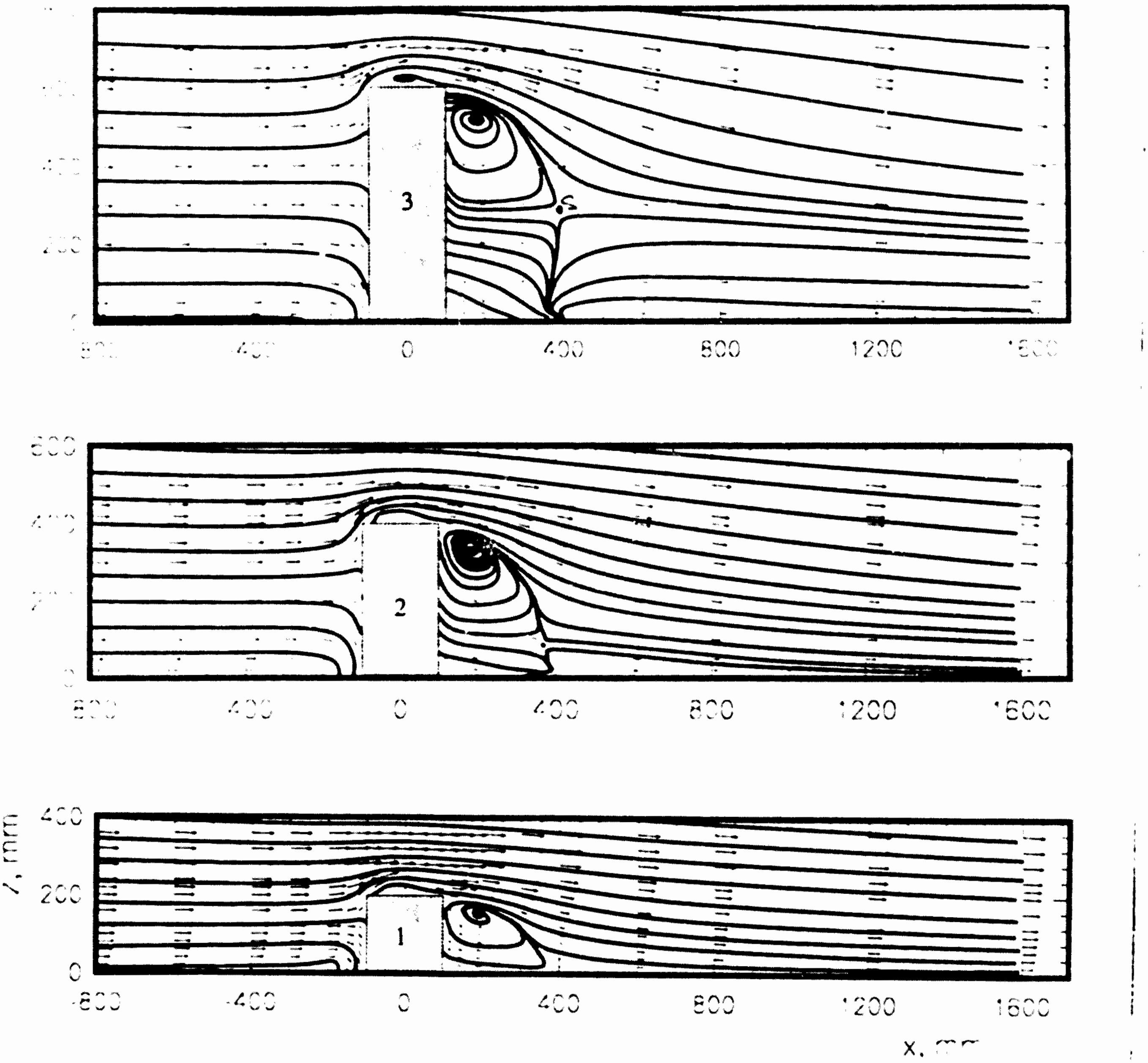

Figure 5. Streamline patterns around buildings of various heights.
Number on building is H/W. L = W.

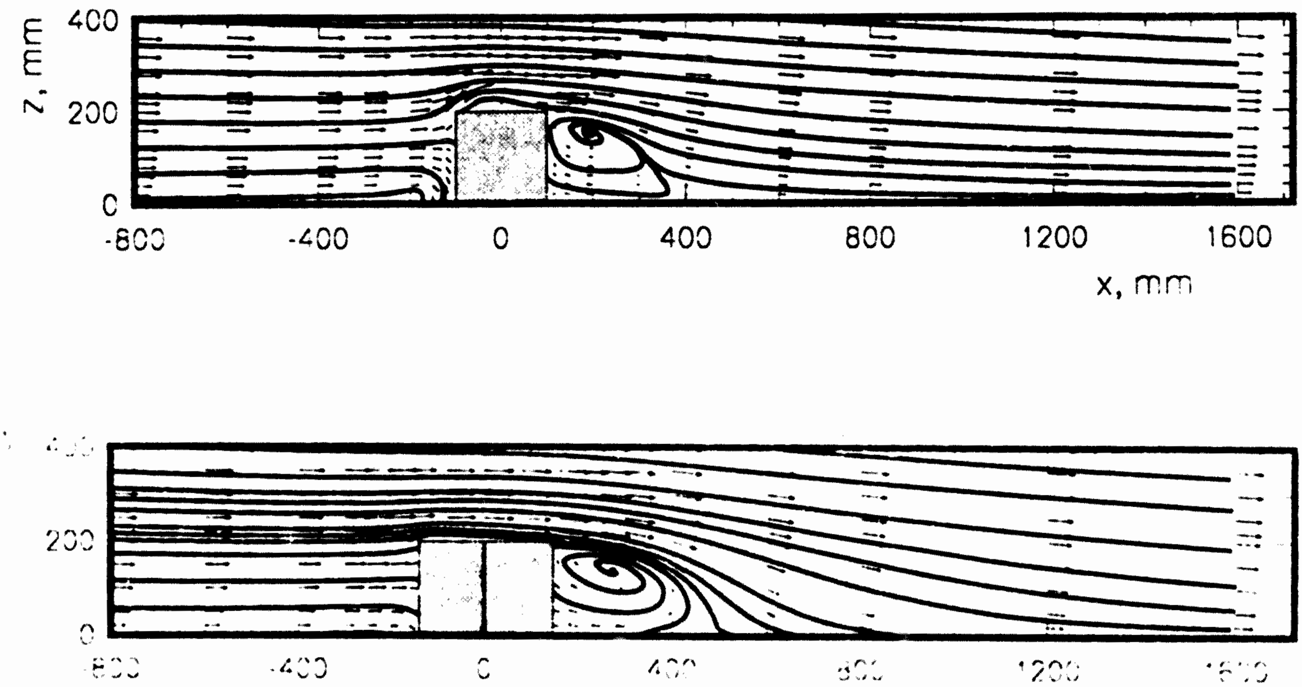

Figure 6. Streamline patterns around a cubical building at 90° and 45° to the wind.

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16. ABSTRACT

Pulsed-wire anemometer measurements have been made in the vicinity of rectangular shaped model buildings immersed in the simulated atmospheric boundary layer of a wind tunnel. The primary purpose of the measurements was to delineate the size and shape of the "cavity" as a function of the building dimensions. The crosswind width, the height and the along-wind length of the building were systematically varied, and the longitudinal and vertical components of the velocity fields were measured in the plane of symmetry (centerplane). For one case, all three velocity components were measured in the full three-dimensional space surrounding the building. These measurements were used to deduce the streamline patterns and, hence, the height and downwind extent of the recirculation zones or cavities and other important features of the flow fields.

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