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NATURE OF AIR FLOW AROUND BUILDINGS

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The interaction of wind with a building results in complex local air motions that significantly affect building occupants, pedestrians and the building itself. Transport of heat, mass and momentum by airflow near the building may perturb the performance of heating, refrigeration and air-conditioning systems and cause a reduction in quality of the internal environment. Unsteady concentrations of linear and angular momentum (jet and vortex motion) near street level result in discomfort and sometimes unsafe conditions for pedestrians. Wind pressures on building surfaces may damage curtain-wall elements and roof coverings and cause malfunction of mechanical systems, such as elevators in tall buildings, through excessive static deflection or oscillatory motion.

Efforts by engineers, architects and meteorologists to develop an understanding of flow around buildings and the physical effects of these flows have become very intense during the last decade. Most of the research work and applications during this period have been reported in the proceedings of national and international conferences.[1-11] Significant scientific progress, trends in applications and needs for further research are summarized in two review papers by Cermak.[12,13] In 1970 the Wind Engineering Research Council (WERC) was formed at a conference[7] held at the California Institute of Technology to stimulate research and coordination of knowledge related to the description of wind and wind effects on buildings, structures and urban areas. Through support of the National Science Foundation, the Council* functions to accomplish this by organizing conferences,[11] forming study panels, and publishing a quarterly newsletter.

The characteristic features of flow around buildings are affected by a host of meteorological and building variables. Significant effects are associated with wind direction relative to the building and vertical distributions of mean speed, turbulence intensity and turbulence scales for the approaching wind. These boundary-layer characteristics are dependent upon the vertical distribution of temperature, upwind surface roughness, the presence of nearby structures, and topographic features. Primary building variables are the geometrical parameters required to describe the building shape. These may be large in number for complex buildings or only two in number for the simplest case of cuboid shapes. Secondary building variables are introduced by architectural details such as parapets and corner details. The great number of possible meteorological-building configurations presented by the building industry and the inability to describe these flows analytically have made the development of organized sets of flow data for use by engineers and architects very difficult. Consequently, only limited sets of flow data for "idealized configurations" such as presented by Halitsky,[14] Evans,[15] and Yang and Meroney[16] are available. As a result, laboratory investigations using small-scale models of the specific building of interest and surrounding buildings in a wind tunnel capable of simulating atmospheric boundary-layer winds have become common practice.[12]

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In these investigations the wind effects--concentrations of dispersed pollutants or wind pressures on the building surfaces--are measured directly rather than attempting to infer them from the local flow characteristics. Development of a data bank of wind effects on buildings rather than of local flow characteristics appears at this time to be of greatest potential use to practicing engineers and architects. However, the basic nature of airflow over buildings must continue to be explored in order to reach a fundamental understanding and correlation of relationships between wind effects and the multitude of relevant meteorological and building variables.

Features of flow around buildings in the following sections will be confined to the "ideal configuration" (reference configuration). The reference configuration is composed of an isolated cuboid building resting on a plane surface subjected to a turbulent boundary-layer wind, without thermal stratification, formed over a plane ground surface of uniform roughness having elements small in size compared to dimensions of the building. The simplest building shape of this general form, the cube, will be given primary consideration. Flow over this reference building illustrates the essential features of flow around all buildings--flow separation, flow reattachment and vortex formation. The primary effect of additional variables is to modify the details of these basic features.

Since flow around buildings is so intimately related to the characteristics of wind in the atmospheric boundary layer some comments on this subject are appropriate. Accordingly, the following section presents some remarks on the nature of wind near the ground. This is followed by comments on the most common, convenient and economical method for obtaining information on flow over buildings--physical modeling. Discussion of this subject is confined to the most highly developed modeling techniques in which boundary-layer wind tunnels are used to simulate the natural wind.

WIND NEAR THE GROUND

The atmospheric or planetary boundary layer is the lowest portion of the atmosphere where motion is significantly affected by frictional forces developed by flow over the earth's surface.[17] As the surface roughness increases from flow over oceans to flow over well-developed urban areas, the boundary-layer depth (gradient wind height) increases from about 300 m to 600 m. Flow in the lowest 100-150 m where flow characteristics are closely related to the local surface fluxes of heat and momentum is designated as the atmospheric surface layer.[18,19] Under rather restrictive conditions the flow in these layers may be described by simple empirical equations. The wind characteristics downwind of large roughness elements such as buildings at heights up to several times the roughness-element height are similar to the characteristics of wakes.[20]

Most of the time, buildings are subjected to winds with boundary-layer or wake characteristics. Exceptions arise in regions of flow separation in the lee of hills and mountains, during severe thunderstorms, in tornadoes, and in the eyewall region of hurricanes.[12]

Atmospheric Boundary Layer for Strong Winds

Atmospheric boundary-layer characteristics for strong winds (speeds in excess of about 10 m/sec at 10 m elevation) are very significant with respect to building aerodynamics. Vertical mixing produced by mechanically generated turbulence during strong wind conditions is sufficient to prevent thermal stratification within the lower part of the boundary layer.[19] Thus, thermally neutral boundary layers (adiabatic lapse rate in the atmosphere and isothermal in the wind-tunnel-simulated natural wind) are of primary interest. The vertical distributions of mean velocity, turbulence intensity and length scales of turbulence for strong winds determine the flow characteristics for most considerations of wind effects on buildings.

Unfortunately, no analytical formulation relating surface roughness to the vertical distribution of mean velocity and turbulence parameters exists even for flow over extensive flat surfaces. The most used form for the distribution of mean wind speed U with height z is a "power-law" expression

$$U/U_g = (z/z_g)^{1/n} \tag{1}$$

where the subscript g refers to values at the gradient-wind height. Fig 1 reveals the nature of this variation for surface roughnesses varying from frictionless (uniform flow with $1/n = 0$)

to roughness elements corresponding to building complexes comprising city centers ($1/n = 0.4$). Selection of a representative profile for a specific building site is possible by using empirical relationships between the surface roughness length z_o, $1/n$, and z_g resulting from the analysis of strong-wind data by Davenport.[21] These relationships are shown in Fig 2.

Even for flow over flat grassland, the common setting for micro-meteorological measurements, turbulence characteristics have not been well-defined throughout the planetary boundary layer. Fichtl and McVehil,[22] using data measured on the 100-m tower at the Kennedy Space Center, have shown that the longitudinal velocity fluctuation spectra $S(n)$ does scale according to the similarity theory of Monin[18]--at least to the 150-m level. The functional form resulting from this scaling when the Richardson number is zero (neutral thermal stratification) is as follows:

$$\frac{nS(n)}{u_*^2} = \text{Const.} \left(\frac{nz}{U(z)}\right)^{-2/3} \quad (2)$$

This form gives a fair indication of the dependence of turbulence on height and is applicable to isolated buildings surrounded by flat terrain of moderate roughness but not to buildings surrounded by the high roughness elements of city centers. An organized description of turbulence developed by flow over upwind building complexes has not been possible. Efforts to simulate atmospheric turbulence by physical modeling in wind tunnels have been motivated as much by this lack of information as by the need to determine the effects of such winds on specific buildings.

The mean pressure measurements on a full-scale building and the small-scale model in a wind tunnel made by Jensen[23] clearly established a strong interdependence between wind-pressure distributions (and consequently local flow features) and boundary-layer characteristics. Accordingly, the nature of flow around buildings must be developed with respect to boundary-layer flows rather than uniform flows in order to obtain useful wind-effect information.

Atmospheric Surface Layer

Wind in the atmospheric surface layer is of major interest because it affects both local diffusion and transport of air pollutants and wind pressures on all buildings of low to moderate heights. Therefore, the characteristics of both weak winds and strong winds are important. For extensive plane surfaces with uniform roughness (elements small compared to thickness of surface layer) and surface heat flux and surface temperature Monin and Obukhov[24] consider the flow statistics to have planar-homogeneity in planes parallel to the surface. They assume that variables affecting the flow structure are height above the boundary z, fluid density ρ, surface shear stress τ_o, surface heat flux H_o, and a stability parameter g/T. These variables may be grouped to give the following scales for velocity, temperature and length in the atmospheric surface layer:

shear velocity $u_* = (\tau_o/\rho)^{1/2}$ (3)

friction temperature $T_* = - H_o/(\rho C_p k u_*)$ (4)

Monin-Obukhov length $L = - u_*^3/[(kg/T)H_o/\rho C_p]$ (5)

The arguments leading to these scaling factors tacitly assume that the flow is fully turbulent and that transport by molecular motions is negligible. Similarity based on these scaling factors is found to exist for flow quantities which are not affected substantially by mesoscale disturbances passing through the flow as may happen for very stable flows.

When the thermal stability does not depart strongly from neutral stability, the dimensionless wind shear $(kz/u_*)(\partial U/\partial z)$ and temperature gradient $(z/T_*)(\partial T/\partial z)$ may be approximated by a linear function of z/L.[24] This formulation leads to the following log-linear distribution forms which can be used to either predict the distribution of mean temperature and velocity or to compare laboratory and field data:

$$U(z) - U(z_{ref}) = u_*/k[\ln(z/z_{ref}) + B_U(z - z_{ref})/L] \quad (6)$$

and

$$T(z) - T(z_{ref}) = T_* [\ln(z/z_{ref}) + B_T(z - z_{ref})/L] \tag{7}$$

These distributions reduce to well-known logarithmic profiles for neutral stability $(L \to \infty)$ when z_{ref} is set equal to z_o.

On the basis of Monin-Obukhov similarity, turbulence statistics in the surface layer can be scaled by the scaling factors expressed by Eq 3, 4 and 5. In particular, the standard deviation of vertical velocity fluctuations may be expressed in the form

$$(\overline{w'^2})^{1/2}/u_* = \phi_1(z/L) . \tag{8}$$

Values of the coefficients for stable and unstable stratifications have been approximated by fitting the functional forms to sets of field data. Many of these results are presented by Panofsky,[25] Lumley and Panofsky,[19] and Kaimal.[26]

Wind in the Wake of a Building

Compared to wind in a boundary-layer flow approaching an isolated building, wind in the wake has a reduction in mean velocity and an increase in turbulence intensity. These quantities have been reported by Peterka and Cermak[20] for the idealized configuration shown in Fig 3.

The measurements shown in Fig 4 and 5 where $W/H = 2.44$ and $D/H = 0.75$ are for the first phase of a systematic investigation of building wakes. These measurements show a large departure of wind characteristics downwind of a building from those associated with the conventional boundary layer. When more than one building is upwind, the wakes interact and more complex flows result. Accordingly, the wind experienced by a building downwind of other buildings cannot be described by the boundary-layer representations of either Eq 1 or Eq 6. At this time physical modeling provides the only practical method for determination of wind characteristics at a building site surrounded by other buildings.

PHYSICAL MODELING OF WIND-BUILDING INTERACTIONS

The primary sources of information on wind effects on buildings and the characteristics of flow around buildings have been measurements on small-scale models with some measurements on full-scale buildings.[27,28] Experimental investigations at both scales will continue to provide the bulk of information on flow around buildings until the fundamentals of flow over bluff bodies and extremely rough surfaces are understood much better than they are presently. A brief review of physical-modeling techniques follows because of its central importance to both basic research and practical applications of building aerodynamics.

Requirements for simulation of the atmospheric boundary layer have been presented and discussed by Cermak and Arya[29] and Cermak[30]. The approximate requirements for "exact" simulation when phase changes of water in the atmosphere and radiational heating or cooling of a particle-laden atmosphere are not of significant effect can be summarized as follows:

(1) scaling of surface geometry without distortion;

(2) equality of corresponding dimensionless parameters for the laboratory and atmospheric flows--Reynolds number $[Re = U_o L_o/\nu_o]$, gross Richardson number $[Ri = (\Delta T)_o L_o g_o/(T_o U_o^2)]$, and Prandtl number $[Pr = \nu_o \rho_o C_{po}/k_o]$;

(3) creation of similar boundary conditions by selection of a length scale L_o and velocity scale U_o to obtain an "aerodynamically rough" surface upwind of the model building and selection of a surface temperature distribution similar to the prototype distribution; and

(4) development of the boundary layer by flow over a sufficiently long distance in a longitudinal pressure-gradient component of zero to produce similarity distributions of mean and turbulent flow characteristics.

Physical modeling of wind effects and flow around a building requires, in addition to simulation of the natural wind, geometrical similarity for the small-scale building.

The meteorological wind tunnel (MWT) shown in Fig 6 designed by Cermak[31] and described by Plate and Cermak[32] meets or approximates the foregoing requirements which are of greatest significance to building aerodynamics. Modeling of dispersion of air pollutants and flow around a building for weak winds with thermal stratification can be accomplished through use of thermal controls in the MWT. The Richardson number can range from -0.5 to +0.5 for a layer of about 0.25 m thick adjacent to the boundary with a boundary-layer depth of about 1.2 m. Elevated inversions can be obtained by cooling the first 10 m of the floor and heating the downstream portion. Simplified wind-tunnel types may be used to meet the essential requirements for strong-wind simulation. Boundary-layer wind tunnels with this capability are shown in Fig 6. The closed-circuit industrial aerodynamics wind tunnel (IAWT) provides a more satisfactory control of flow than the open-circuit environmental wind tunnel (EWT). Accordingly, when laboratory space permits, the closed-circuit type wind tunnel should be used. Boundary-layer thicknesses up to 1.2 m over the downstream 5 m of the test section can be obtained in both the EWT and IAWT with addition of boundary-layer stimulators at the test-section entrance.

Many wind tunnels have been built throughout the world to provide a capability for small-scale model studies of aircraft. In most instances the aeronautical wind tunnel has a test-section length only one or two times the cross-section diameter or width and hence does not provide a satisfactory facility for the investigation of building aerodynamics. On the other hand, only a few facilities of the types shown in Fig 6 of sufficient size for satisfactory study of wind effects on buildings are known to the author. The MWT at Colorado State University is the only one of this type in existence. Facilities of the IAWT type (closed return) have been constructed at many universities in the U.S. The largest facilities of this type are at California Institute of Technology, Colorado State University, Illinois Institute of Technology, Iowa State University, University of Michigan, and Virginia Polytechnic University, to name those that have engaged in substantial wind-engineering efforts. In the U.S., organizations that have constructed facilities of the EWT type (open return) include Calspan Corporation, Colorado State University, Environmental Protection Agency, Iowa State University, New York University, Oregon State University, and the University of Notre Dame.

When modeling flow around buildings in the wind tunnels referred to in Fig 6, length scales depend upon the actual building size and range from 1:100 to 1:500. The maximum ambient wind speeds U_∞ corresponding to the gradient wind U_g range from 10 to 40 m/s in the usual boundary-layer wind tunnel. Accordingly, the Reynolds number for a building model is 100 to 1000 times smaller than the prototype value. This relaxation of the requirement of equal Reynolds numbers does not present a barrier to modeling of the atmospheric boundary layer or flow around a building. When the wind-tunnel Reynolds number $U_o L/\nu_o$ is sufficiently large; (L is the test-section length), and the relative roughness L/K_s based upon an equivalent sand roughness of particle diameter K_s is sufficiently small, the surface drag coefficient becomes independent of $U_o L/\nu_o$. Thus, if in addition the boundary is sufficiently long to achieve an equilibrium state (about 10 m), the modeled boundary layer attains a structure similar to the full-scale structure.[12] Flow around a sharp-edged model building will be similar to the prototype flow if the building Reynolds number exceeds 11,000; i.e., according to Halitsky,[33] the separation cavity and vortex structure become invariant in form at this Reynolds number. When building surfaces are curved, roughening of the model surface can result in correct flow patterns as inferred from model studies of cooling towers by Armitt.[3] However, much research remains to be done before this technique can be used with complete confidence.

The effects of thermal stratifications can be made similar by attaining equality of the Richardson number between model and prototype. Richardson numbers found in the atmosphere can be obtained easily in the MWT. In wind tunnels using air as the fluid, Prandtl-number equality is automatically achieved.

CHARACTERISTIC FEATURES OF WIND NEAR BUILDING SURFACES

A building interacts strongly with the oncoming wind to produce regions of complex flow adjacent to the building surfaces. The basic flow features in these regions consist of separation cavities and vortices. These characteristic features for the idealized configuration are discussed in the following paragraphs.

Flow Characteristic

Typical regions of separated flow found around tall and moderately tall buildings of rectangular cross section are shown in Fig 7(a).[13] Superimposed upon the horizontal motion is a vertical motion on the upwind face induced by vertical pressure gradients arising from the mean wind-speed gradient. Vertical motion on the downstream face is induced by the low mean pressure arising from separation over the building roof. These vertical motions are indicated in Fig 7(b). The associated wind pressures around a typical cross section are given in Fig 8.[36] Sketches of typical flow patterns around buildings of different geometry for the idealized configuration are given by Baines[1] and Halitsky[34].

Details of air movement near a building are most easily obtained by flow visualization using a small-scale model. Smoke introduced at points on the model surface clearly reveal the air motion and circulation of air pollutants released from vents. Using this technique, the geometry of separation cavities and vortices can be readily identified and recorded[14,16,34,35]--see Fig 9, 10 and 11.

Surface Wind Effects on Buildings

Air movement around buildings, in addition to transporting air pollutants from one location on the building to another, results in non-uniform distributions of mean and fluctuating local pressures as well as heat-transfer rates. Of all the surface effects, most of the available information pertains to wind pressures. The focus on wind pressures has been motivated by needs for these data in the design of buildings and by the importance of pressures for basic fluid-dynamical considerations.

Detailed surface-pressure data obtained by Peterka and Cermak[36] for one cross section of a tall building (H/W = 4.1), essentially isolated on a plane surface, and subjected to a boundary-layer wind are shown in Fig 8. The flow pattern for this wind direction of $\alpha = 15°$ is shown in Fig 7(a). Mean, rms and peak pressure coefficients given in Fig 8 are defined as follows:

$$\text{mean,} \quad C_p = \frac{(p-p_\infty)_{mn}}{\frac{1}{2}\rho U_\infty^2} \; ;$$

$$\text{rms,} \quad C_{p_{rms}} = \frac{(p-p_\infty)_{rms}}{\frac{1}{2}\rho U_\infty^2} \; ;$$

$$\text{peak,} \quad C_{p_{min}} = \frac{(p-p_\infty)_{min}}{\frac{1}{2}\rho U_\infty^2} \quad \text{and}$$

$$C_{p_{max}} = \frac{(p-p_\infty)_{max}}{\frac{1}{2}\rho U_\infty^2}$$

where p is the instantaneous surface pressure and p_∞ is the reference pressure in the undisturbed flow above the building. The reference dynamic pressure $\rho U_\infty^2/2$ is the value corresponding to the undisturbed flow speed above the building; however, this reference is often taken to be $\rho U_H^2/2$ in which U_H is mean wind speed at the building height H. The latter can be much smaller than the former; therefore, care must be exercised when using pressure coefficients that are not explicitly defined.

Several significant details of the data shown in Fig 8 are typical and should be noted. On building faces where the flow is completely separated (no reattachment) and the outer streamlines of the cavity are not sharply curved, as on faces 3 and 4, mean pressures are negative and essentially constant. This is true for entire side surfaces on low buildings as shown for side 4 in Fig 9 and sides 1 and 4 in Fig 10.* When separation occurs followed by

*Pressure data in Fig 10 and 11 are unpublished information obtained by R. E. Akins, Graduate Research Assistant, Colorado State University, in a systematic investigation of wind pressures on buildings under a grant from the National Science Foundation.

reattachment as for face 1 in Fig 8 mean pressures are very non-uniform over the face and extremely high pressure fluctuations occur near the upwind corner. This highly disturbed flow that can occur at all corners as the wind direction α varies, can cause much distress to cladding, poor operation of ventilating systems and high heat-transfer rates. Wind-tunnel investigations reveal that as turbulence intensity of the approaching wind increases the reattachment location moves upwind toward the corner.[37] Unfortunately, little information on heat-transfer rates for building surfaces subjected to turbulent shear flows is available. Development of this knowledge should be undertaken as a systematic research effort. The results of Kestin[38] indicate that heat-transfer rates at stagnation regions (face 2, Fig 8) can be expected to increase as turbulence intensity in the approaching wind increases.

Dispersion characteristics and pressures on the roof of a cuboid building are strongly affected by the wind direction α. When the wind direction is in the range $0 \leq \alpha < 40°$ a cavity of the type shown in Fig 9 develops. As α increases from 40° through $\overline{4}5°$ a pair of vortices forms on the roof surface as shown in Fig 11. Formation of the vortices destroys the roof cavity (see Fig 10) and results in very low pressures near the upwind corner. The former effect is favorable with regard to transport of pollutants released at roof level but the latter effect often initiates failure of the roof covering. Definition of roof-cavity geometry as a function of wind direction and building geometry remains as a task for future research. The effects of parapets and horizontal projections on both the cavity and vortex formation should be investigated in an effort to find architectural detailing which will promote roof-top diffusion while not subjecting the roof to unusually low wind pressures.

Relationships Between Mean Pressure Distributions and Flow Near a Building Surface

A large body of data describing mean pressure distributions on buildings subjected to simulated natural winds is available in reports describing wind-tunnel investigations of specific buildings. Systematic investigations of wind pressures on full-scale buildings[28] and on small-scale buildings have been reported[39] or are currently in progress by Akins, Peterka and Cermak (Paper III-2).[11] These data are useful for evaluation of natural ventilation through a building, estimation of infiltration rates, predicting the operational characteristics of forced ventilation systems, and for building design purposes. However, as described in the following paragraph, the mean pressure distributions can also be useful for estimating the direction of mean flow near the building surfaces for given wind directions.

By comparing the flow pattern in Fig 7(a) with the mean pressure distribution given in Fig 8 some correlations between flow direction near the surface and the mean surface-pressure gradient becomes apparent. For example, on faces 1 and 2 where the pressure gradients are large, flow near the surface is in the direction of decreasing pressure. Where pressure gradients are weak or nearly zero as on faces 3 and 4, flow near the surface is induced through action of turbulent shear at the outer edge of the separation cavity and the surface-pressure gradient no longer determines the surface flow direction. Similar correlations may be noted in Fig 9, 10 and 11; however, some difficulty in interpretation of the steady-state smoke photographs is experienced because smoke far from the surface obscures the near-surface flow.

Accordingly, a useful indicator of near-surface flow direction is the direction of decreasing mean surface pressure when the pressure gradient is strong enough to dominate the fluid motion. The indications obtained in this manner are consistent with observations--near-surface flows move toward edges where separation occurs and away from stagnation regions.

CONCLUSIONS

The nature of airflow around a building is determined primarily by the characteristics of wind approaching a particular site, the geometry of surrounding buildings and topography, and geometry of the building itself. Variables describing these features represent an extremely large set of possible meteorological-building configurations for which detailed flow characteristics have not been investigated systematically.

Strong mean winds approaching an "ideal configuration" may be described by a power-law variation with height, whereas winds significantly influenced by thermal stratification follow a log-linear distribution. Surrounding buildings introduce wakes that interact with the atmospheric boundary-layer to produce very complex winds. Although no analytical description of these winds is available, they can be reproduced in boundary-layer wind tunnels. The simulated winds may be utilized to make measurements of wind characteristics or to investigate the nature of flow around an individual building and the associated wind effects of heat, mass and momentum transport.

Flow around a building is ordinarily a composite of stagnation zones, regions of flow separation and regions of vortex formation. These flows result in large pressure differences over the building surfaces that induce secondary flow around the building. Strong vertical circulation is induced on the upwind and downwind faces of a building. This motion can transport air pollutants from street level, over the building surface, and onto the building top.

Wind effects of primary importance caused by flow around a building are surface wind pressures, circulation of air from one location on the building to another, and surface heat transfer. Variation of pressure distributions and magnitude with wind direction and speed can produce large effects on the loading, control, and efficiency of heating and cooling systems. The circulation can cause air pollutants released from stacks, flues, vents, and cooling towers to reenter the building through ventilation and air-conditioning inlets. An examination of mean surface-pressure gradients on a building surface can provide valuable information on circulation characteristics; however, flow visualization and the measurement of tracer-gas concentrations on small-scale models yield the most reliable information.

Little information on heat-transfer rates for exterior building surfaces is available. In view of the need to design for energy conservation, research on this subject should be given high priority.

NOMENCLATURE

B_T	coefficient, dimensionless
B_U	coefficient, dimensionless
C_p	specific heat at constant pressure, J/(kg·K)
D	least horizontal dimension of rectangular building, m
g	gravitational acceleration, m/s^2
H	height of building, m
H_o	heat flux at surface (z = 0), W
k	von Kármán constant, dimensionless
K_s	equivalent sand-roughness diameter of surface roughness, m
L	Monin-Obukhov length or test-section length, m
n	frequency, Hz
1/n	exponent for "power-law" distribution of mean velocity, dimensionless
p	pressure, N/m^2
Re	Reynolds number, dimensionless
Ri	Richardson number, dimensionless
S(n)	energy spectrum of longitudinal velocity fluctuations, m^2/s
T	temperature, °C
T_*	friction temperature, °C
u_*	friction velocity, m/s
U	mean wind speed, m/s
w'	standard deviation of vertical velocity fluctuations, m/s
W	largest horizontal dimension of building, m

x horizontal space coordinate, m

y horizontal space coordinate, m

z vertical space coordinate, m

z_o surface roughness length, m

Greek Symbols

α angle between normal to building side and mean wind, rad

δ boundary-layer thickness, m

ν kinematic viscosity of air, m^2/s

ρ mass density, kg/m^3

τ_o surface shear stress, N/m^2

ϕ_1 function, dimensionless

Subscripts

g quantity at gradient-wind height

H quantity at building height

o reference quantity

rms root-mean-square

∞ quantity at height δ

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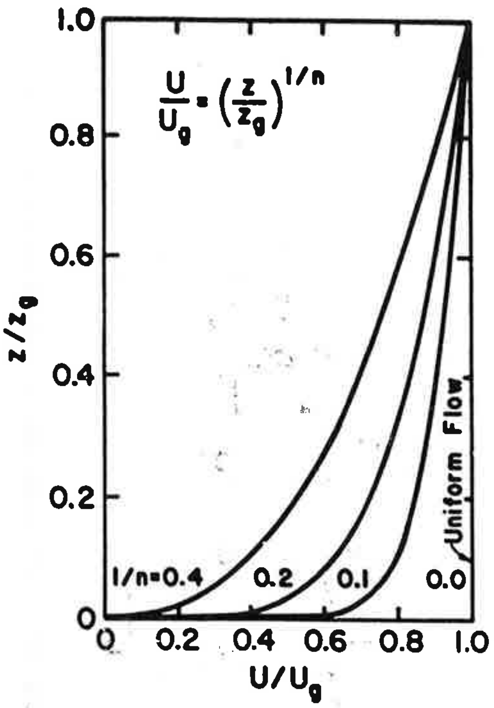


Fig. 1 Mean wind speed distributions for the atmospheric boundary layer during strong winds

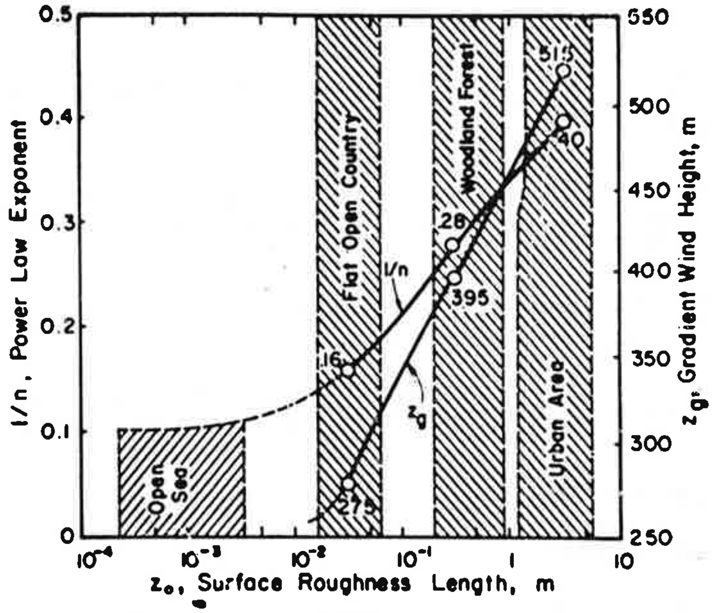


Fig. 2 Wind-profile parameters for strong winds over surfaces of different roughnesses (21)

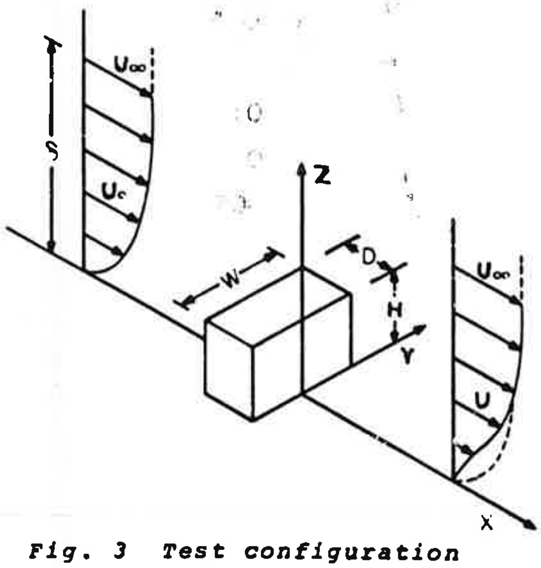


Fig. 3 Test configuration and nomenclature

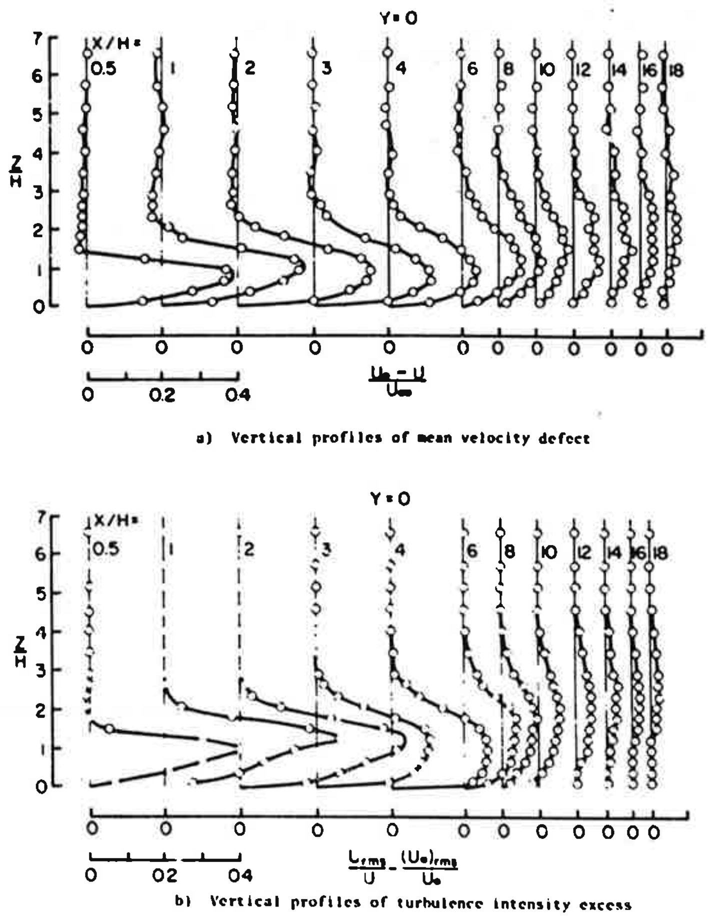
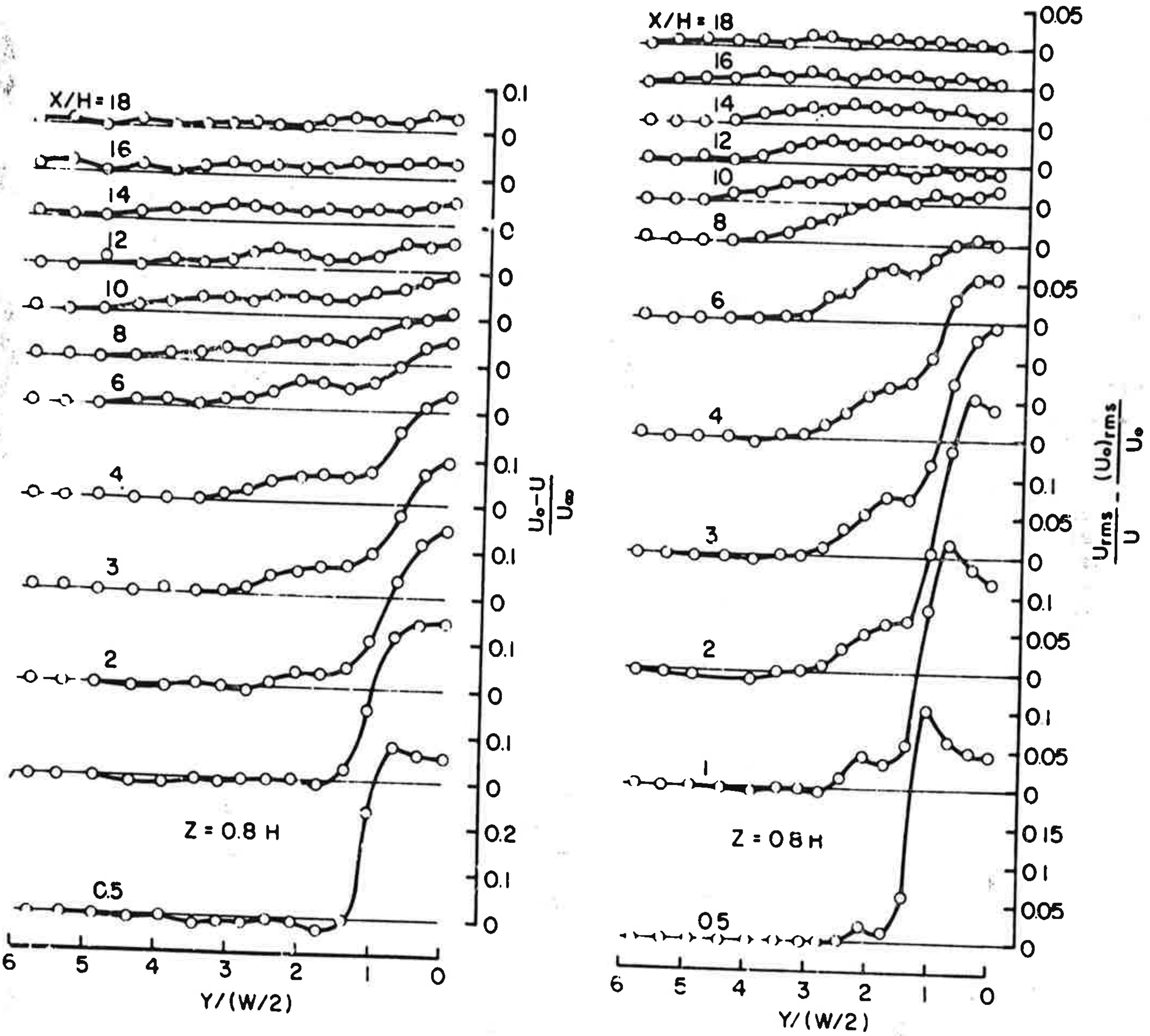


Fig. 4 Wake characteristics for an isolated cuboid building - W/H = 2.44; D/H = 0.75; δ/11 = 9.4; 1/n = 0.24



a) Horizontal profiles of mean velocity defect

b) Horizontal profiles of turbulence intensity excess

Fig. 5 Wake characteristics for an isolated cuboid building - W/H = 2.44; D/H = 0.75; α = 0; δ/H = 9.4; 1/n = 0.24

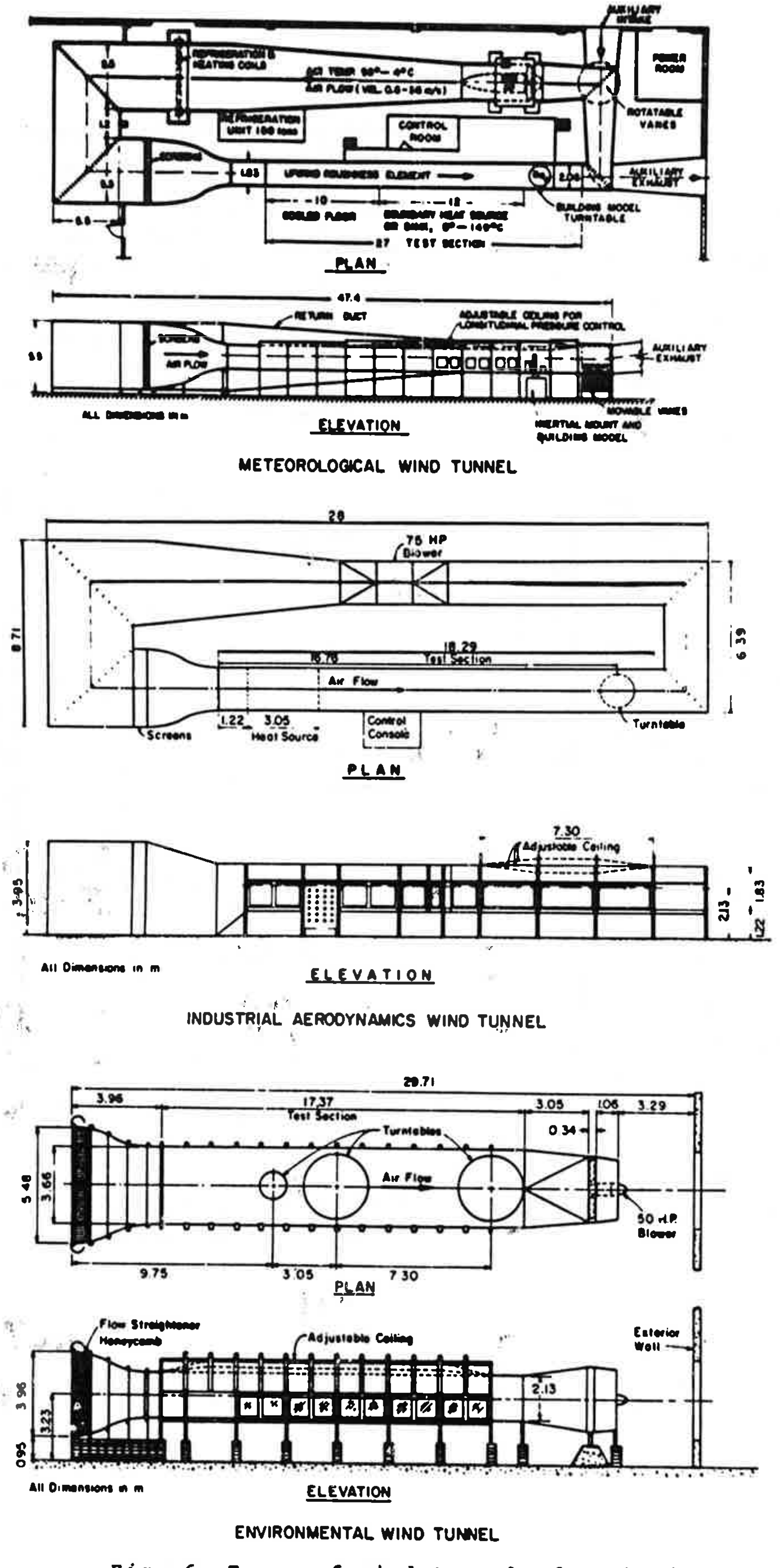


Fig. 6 Types of wind tunnels for physical modeling of flow around buildings - fluid dynamics and diffusion laboratory, Colorado State University

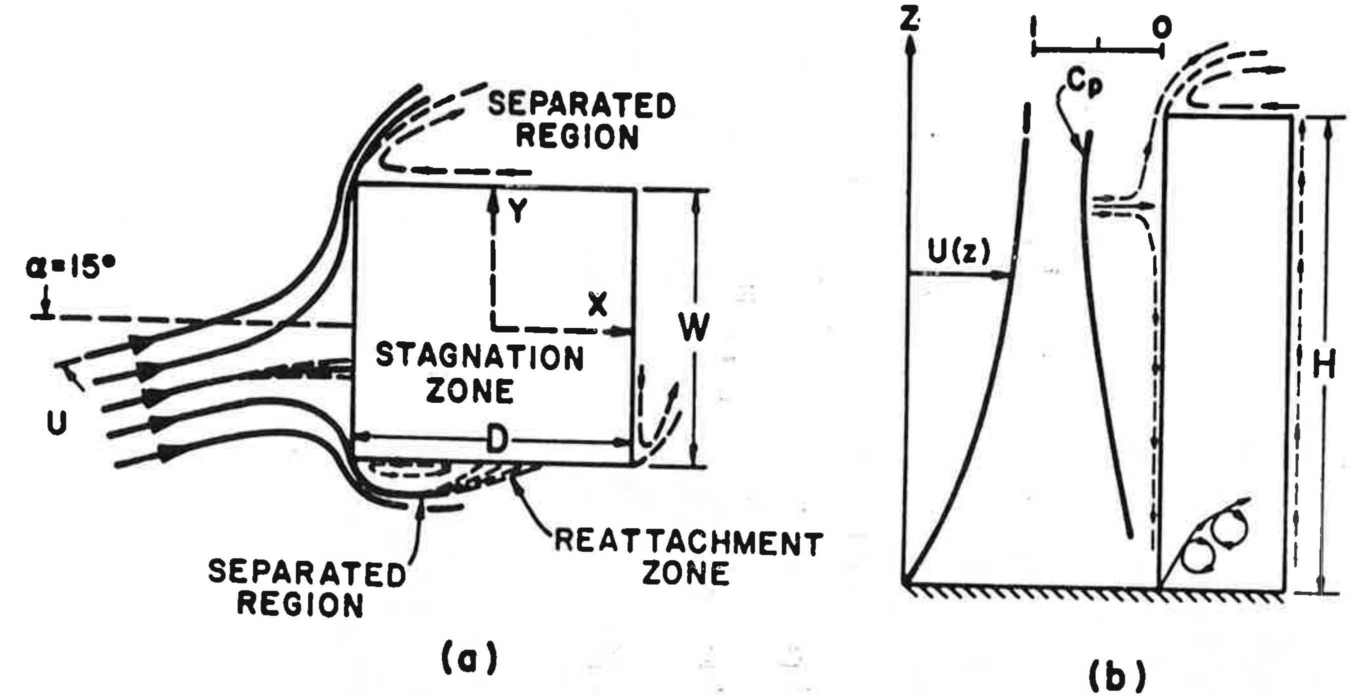


Fig. 7 Typical flow pattern near a square prism in a boundary layer

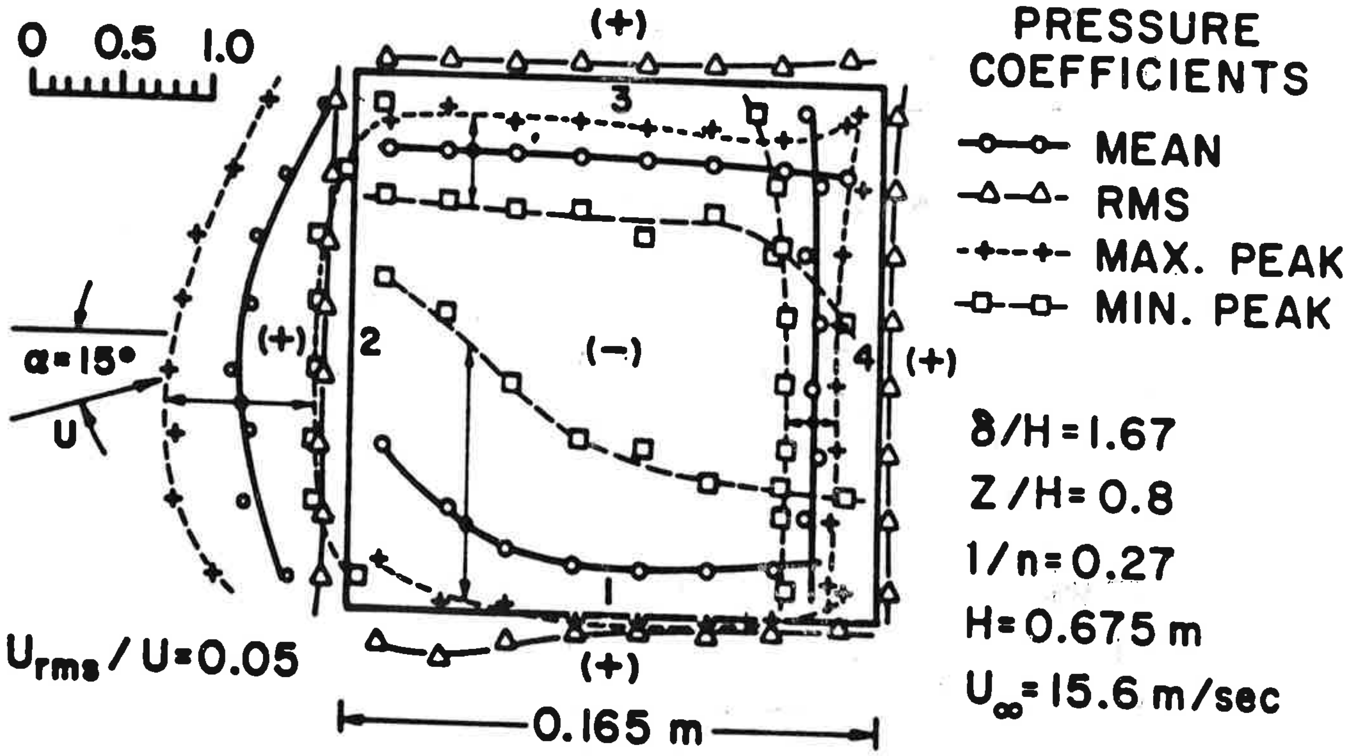


Fig. 8 Pressure coefficients determined from measurements on a 1:300 scale model block building in a boundary-layer wind tunnel by Peterka and Cermak (36) - reference pressure = $\rho\ U_\infty^2/2$

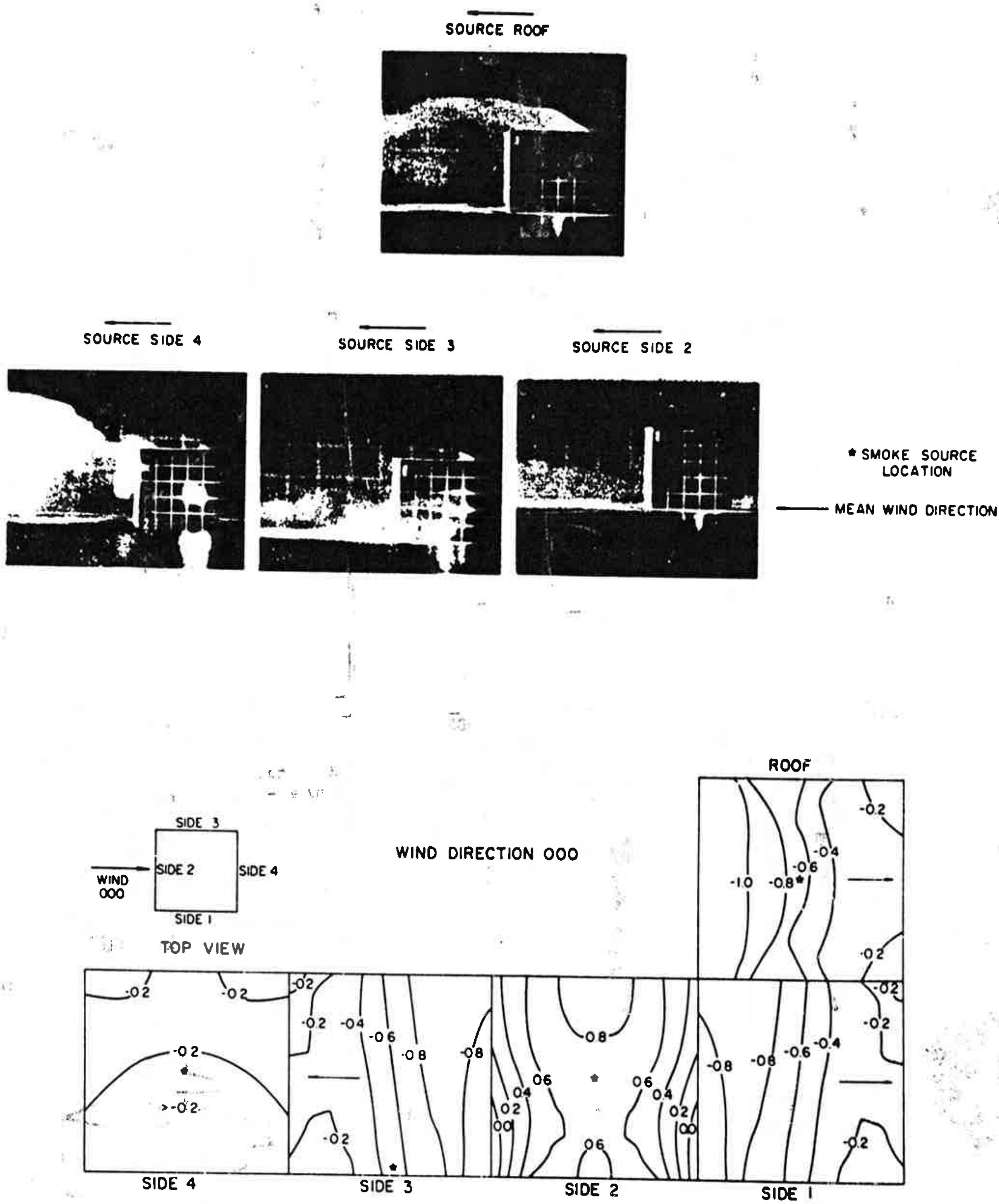


Fig. 9 Mean pressure coefficients and flow visualization (16) for boundary-layer flow over an isolated cube--reference pressure = $\rho\, U_H^2/2$*;* $\delta/H = 4.8$*;* $1/n = 0.24$

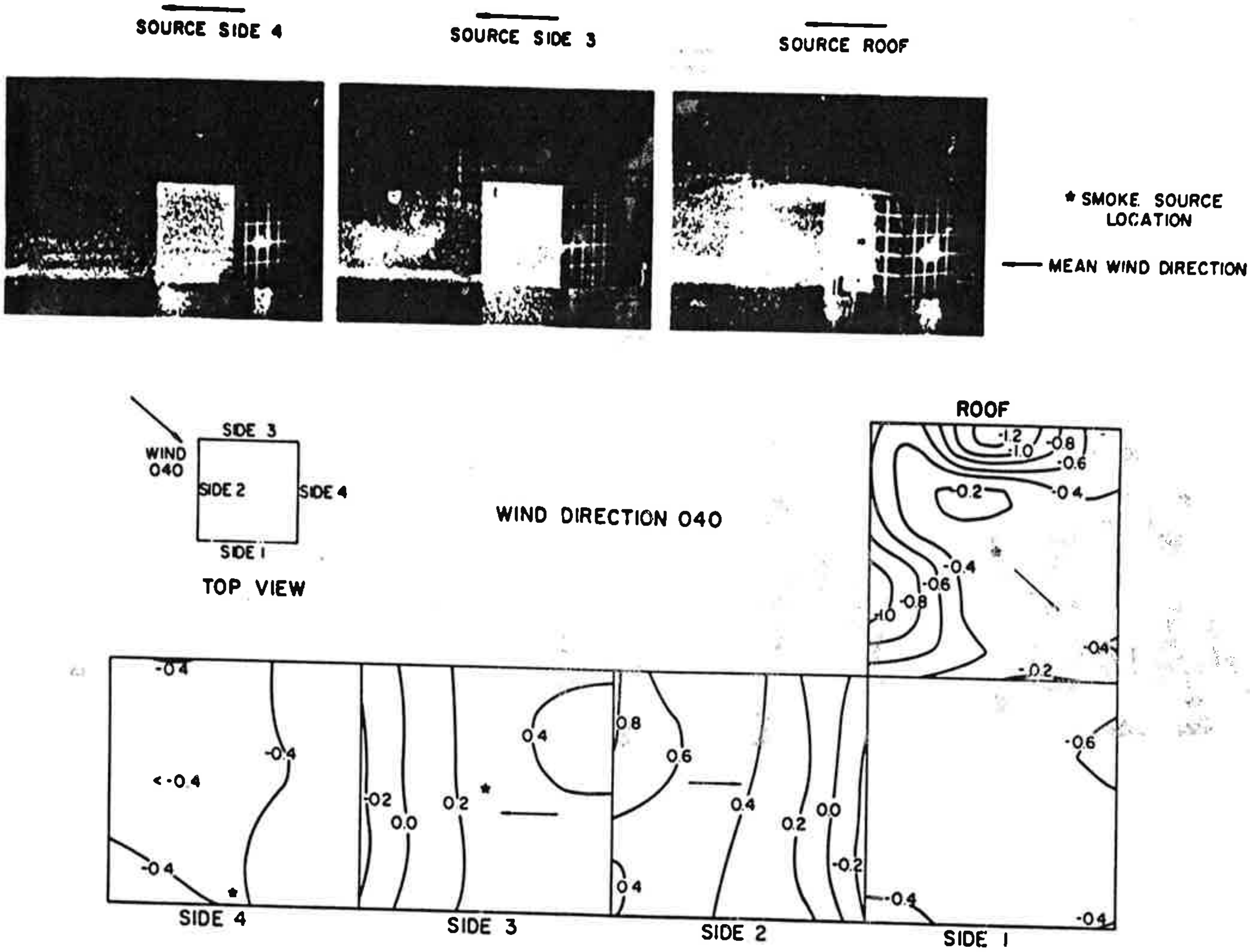
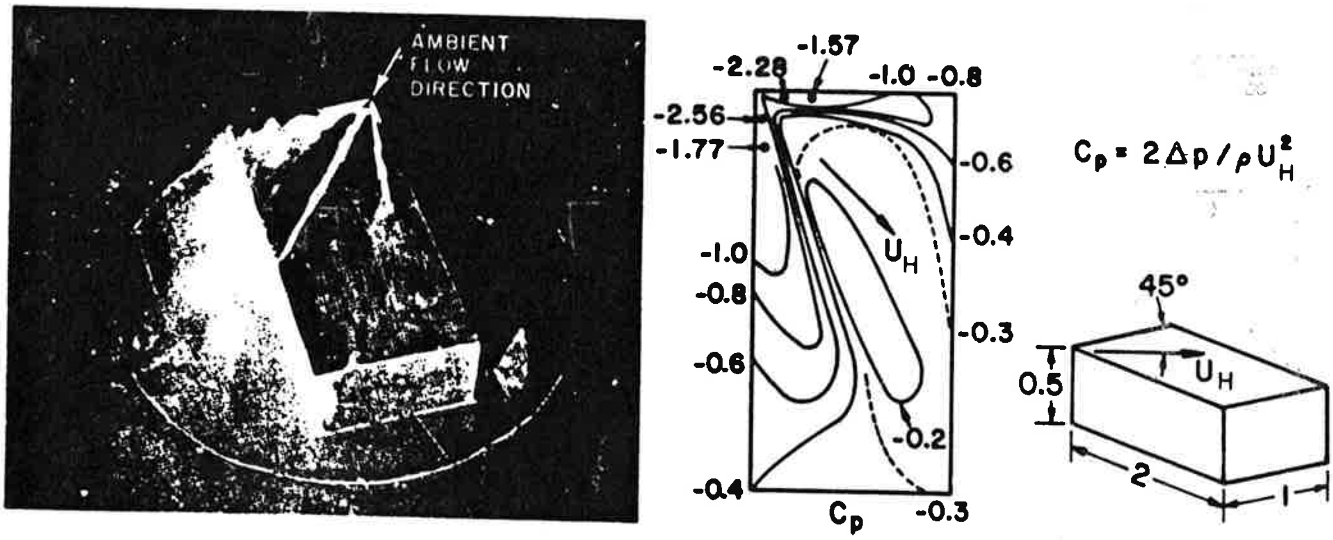


Fig. 10 Mean pressure coefficients and flow visualization (16) for boundary-layer flow over an isolated cube--reference pressure = $\rho U_H^2/2$; $\delta/H = 4.8$; $1/n = 0.24$



a) Smoke visualization of vortex formation (35)

b) Mean pressure coefficients (39)

Fig. 11 Vortex formation and mean pressure coefficients on the roof of a cuboid building for α = 45 deg