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Applications of Wind Tunnels to Investigation of Wind-Engineering Problems

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Nomenclature

A_2 = torsional-stability aerodynamic coefficient
C_p = specific heat at constant pressure
d_p = diameter of particle
D = stack diameter
e = coefficient of restitution
f = natural frequency of building
g = gravitational acceleration
h = source height
H = height of structure
k = thermal conductivity of fluid or concentration coefficient
K = wave number
K_c = eddy diffusivity for contaminant
K_M = eddy diffusivity for momentum
L = reference length
p = pressure
Q = emission rate
t = time
T = mean temperature
ΔT = temperature difference
u_f = terminal fall velocity of particle
U = mean velocity
V_s = exit speed of stack emissions
x = longitudinal coordinate
y = lateral coordinate
z = vertical coodinate
z_0 = roughness length
α = wind direction
δ = boundary-layer thickness
ϵ = energy dissipation rate per unit of mass
ζ = dimensionless height (z/z_0)
ρ = mass density
θ = potential temperature
μ = dynamic viscosity
ν = kinematic viscosity
χ = concentration of contaminant
ω = angular velocity
Ω = angular velocity of coordinate system

Subscripts

g = quantity at geostrophic level
0 = reference quantity
s = quantity associated with structure

Superscripts

$(\ )^*$ = nondimensional quantity
$\overline{(\ )}$ = time average

I. Introduction

ALTHOUGH the activities and works of mankind have always been affected by wind, identification of wind engineering as a distinct discipline has been made only within the last decade. In a review of applications of fluid mechanics to wind engineering the author[1] notes that this identification occurred in 1970 at a conference on wind loading of structures.[2] In general, wind engineering may be described as the rational treatment of interactions of wind in the atmospheric boundary layer with activities and works of mankind on the surface of Earth. This definition encompasses a wide range of problems, excluding most aeronautical engineering applications, that can be studied with the aid of appropriate wind tunnels.

Wind-engineering problems discussed in the following sections may be placed in one of three categories—1) wind forces on buildings and structures, 2) mass transport by wind, or 3) features of local wind—for which physical modeling in wind tunnels has become an accepted method of investigation.

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Measurements on physical models to treat problems in the first category include mean and fluctuating pressures, forces, moments, deflections and accelerations. In the second category, measurements of mean and fluctuating concentrations of toxic or flammable gases and particulates are often necessary. The third category of problems may require measurement of mean wind velocities, turbulence intensities, turbulence energy spectra, or turbulence scales for their treatment. A substantial body of literature on the use of wind tunnels for investigation of these and other problems has been referenced in several reviews.[1,3-8] Conferences and symposia since 1963[2,9-18] contain many additional contributions to the wind-engineering literature. In the following presentation, attention will be focused on the application of wind tunnels to wind-engineering problems of greatest current concern.

The use of physical modeling in wind tunnels is equally (perhaps more) important to the development and practice of wind engineering as it has been for aeronautical engineering. Whereas many aircraft design functions now can be accomplished with the aid of modern computers, the same is not yet true for most wind-engineering problems. The great dependence by wind engineers on physical modeling lies in the extreme complexity and variability imparted to wind in the atmospheric boundary layer as it moves over cities, terrain features, forests, lakes, etc. Accordingly, the first requirement for physical modeling of wind effects is to simulate natural winds in the laboratory. This requirement has necessitated the development of special wind tunnels.

II. Wind Tunnels for Simulation of the Atmospheric Boundary Layer

Wind tunnels for aeronautical research and testing are usually designed to provide a test-section flowfield of uniform mean velocity and temperature and a low level of turbulence. On the other hand, wind tunnels for wind-engineering investigations must be able to provide a boundary-layer-type flow in which the turbulence characteristics, mean velocity, and mean temperature distributions can be varied to simulate the wide range of flow structures that occur in the atmospheric boundary layer. The approximate range of length-to-depth ratios for the aeronautical wind tunnels is 1-5, whereas the desirable range is 10-15 for the wind-engineering type. Requirements for attaining a satisfactory simulation of the atmospheric boundary layer will be reviewed briefly and wind tunnels that meet these requirements will be described.

Requirements for Similarity

Basic requirements for simulation of the atmospheric boundary layer in a wind tunnel have been established by the writer[19] through inspectional analysis of the conservation equations and comparison of laboratory and full-scale micrometeorological data. Most considerations of wind effects on buildings and structures are for strong wind conditions where thermal stratification of the atmosphere is destroyed by intense vertical mixing. Accordingly, for this category of wind-engineering problems only physical modeling of neutral atmospheric boundary layers by isothermal wind tunnel boundary-layer flows is necessary.[20] However, physical modeling of mass transport by wind requires simulation of thermal stratification associated with the atmospheric boundary layer.[19,21]

The basic requirements for simulating strong natural winds to study wind effects on buildings and structures are: 1) undistorted scaling of boundary geometry, including topographic features and buildings; 2) Reynolds number (U_0L_0/ν_0) equality; 3) Rossby number $(U_0/L_0\Omega_0)$ equality; and 4) kinematic similarity of approach flow, i.e., distributions of mean velocity and turbulence characteristics.

For most cases, the exact requirement of equal Reynolds numbers for model and prototype must be compromised. Geometrical scale ratios are commonly in the range of 1:500-

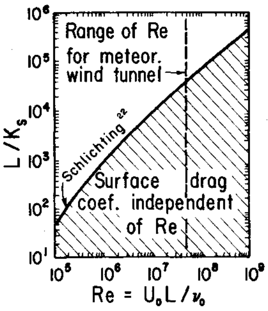


Fig. 1 Reynolds-number independence of the surface drag coefficient as a function of relative roughness in neutral flow.

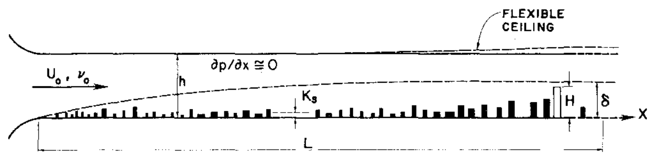


Fig. 2 Long-test-section wind tunnel ($L/h > 12$) for natural development of boundary-layer characteristics for site.

1:100; therefore, unless a compressed-air wind tunnel or a facility using fluid such as freon is used, the laboratory Reynolds number will be smaller than that for the prototype. This compromise of Reynolds number equality is not a deterrent to modeling since the flow over rough boundaries becomes invariant well below the range of Reynolds number achieved in the wind tunnels to be described. Reynolds-number independence of the surface drag coefficient as shown in Fig. 1 is the criterion used to determine if the wind tunnel Reynolds number is large enough for flow invariance.

Large wind tunnels cannot be rotated easily; therefore, the requirement of equal Rossby numbers must be relaxed. Rotation of Earth causes the mean wind to change direction by about 5 deg over a height of 200 m for internal boundary layers developed by strong winds over rough boundaries. No measurable rotation of the mean wind vector occurs for the large Rossby numbers of wind tunnel boundary layers.

Kinematic similarity of the approach flow can be achieved by an appropriate wind tunnel. The wind tunnel must be capable of developing a turbulent boundary-layer thickness δ from 1 to 2 times as great as the height of the modeled structure H. If this can be accomplished and the ratio of upwind surface roughness z_0 to structure height H is equal for model and prototype, Jensen[23] demonstrated by measurements on both a model and prototype box-like structure that the mean pressure distributions are similar. Use of these criteria for sharp-edged structures leads to a desired test-section length of from 25 to 35 m when studies are to be made on tall buildings up to 300 m high, modeled on scales of from 1:600-1:400. An additional requirement is that the pressure be essentially constant along the mean flow direction, as it is in the atmosphere. This requirement may be met by providing adjustment of the cross-sectional area of the test section—usually accomplished through use of a flexible ceiling that can be raised several feet from the position of parallelism with the floor. A schematic representation of a wind tunnel test section that can meet the foregoing requirements is shown in Fig. 2.

For studies of mass transport, thermal stratification of the atmospheric boundary layer must also be simulated. This can be achieved by requiring that the gross Richardson number $Ri = (\Delta T)_0 L_0 q_0 / (T_0 U_0^2)$ and the Prandtl number $Pr = (\nu_0 \rho_0 C_{p0}) / k_0$ be equal for model and prototype.[19] Equal values of Ri for a wide range of atmospheric conditions can be achieved at the scales commonly used—1:200 to 1:10,000—if the test-section floor and air in the return circuit can be either heated or cooled sufficiently to produce values of $(\Delta T)_0$ up to 100°C and the wind speed U_0 can be con-

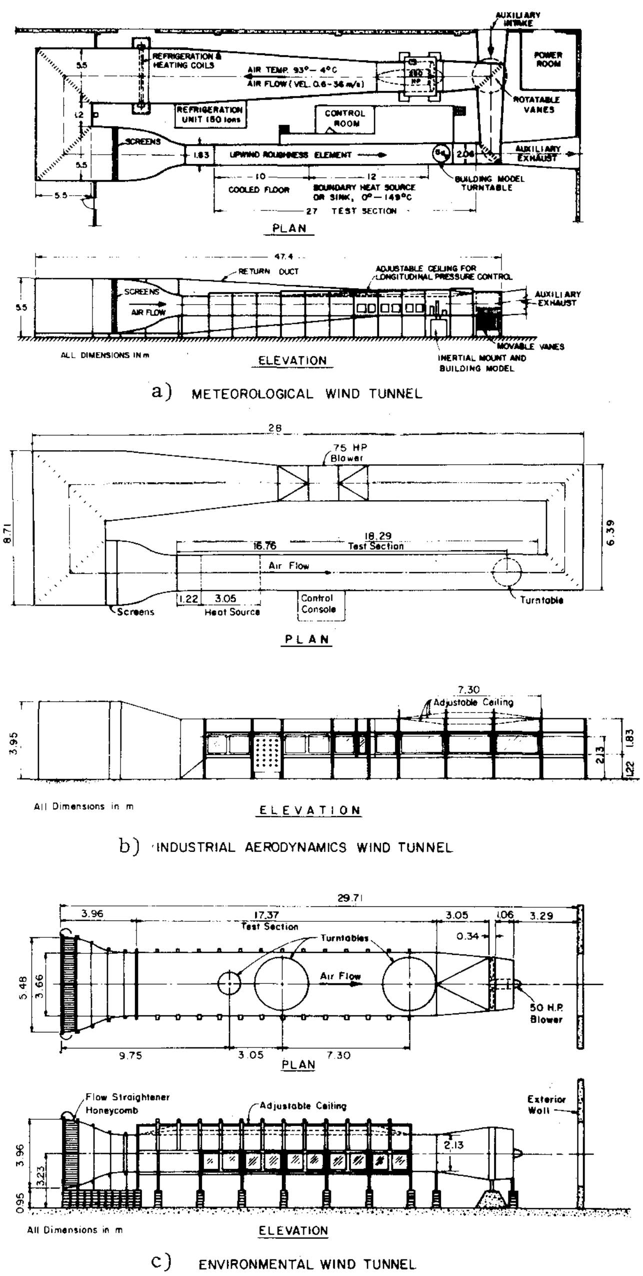


Fig. 3 Types of wind tunnels for physical modeling of the atmospheric boundary layer FDDL, Colorado State University.

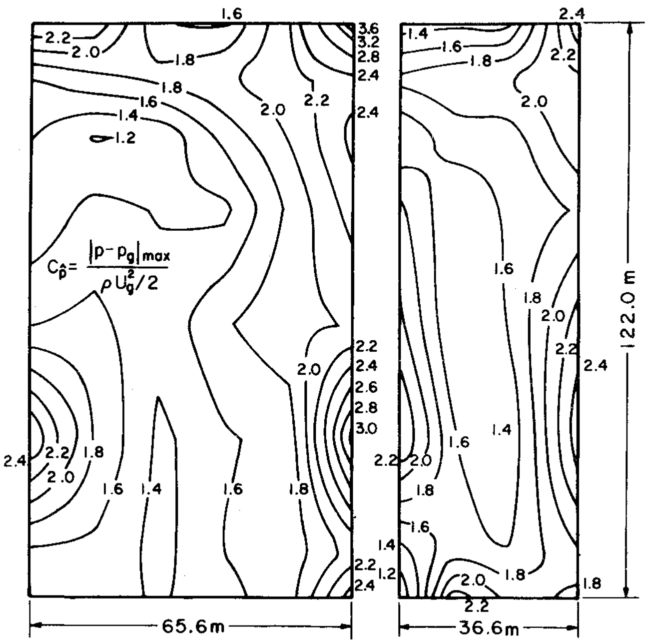


Fig. 4 Absolute peak-pressure coefficients for two sides of a rectangular building.

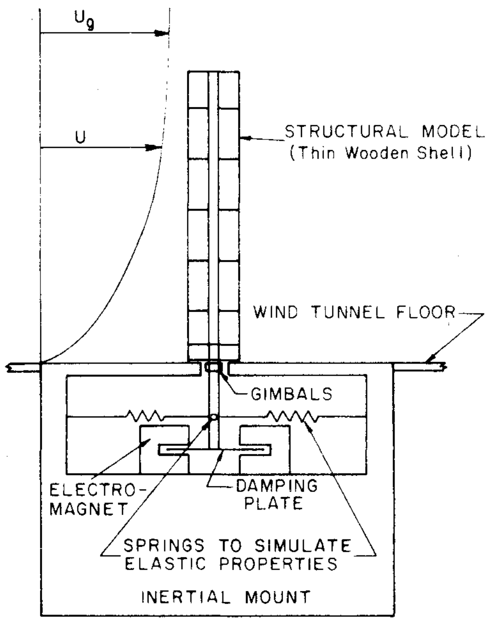


Fig. 5 Schematic representation of a primary-mode aeroelastic building model with two degrees-of-freedom.

trolled down to about 0.5 m/s. Prandtl number equality is satisfied in wind tunnels using air near atmospheric pressure as the working fluid.

Wind Tunnel Types and Characteristics

The first meteorological wind tunnel (MWT) was designed by Cermak [24] to simulate both neutral and thermally stratified atmospheric boundary layers, and is shown in Fig. 3a. Temperature control of the lower boundary of the test section and the ambient air permits simulation of many types of thermal stratifications. Therefore, studies of atmospheric diffusion as well as strong wind effects on structures are possible. The recirculating capability provides optimum control of both wind speed and temperature while the long test section develops thick boundary layers with characterisics consistent with the upwind boundary features. In this tunnel, boundary layers up to 1.2 m in thickness at wind speeds near 40 m/s can be developed at the downstream position of the test section where the models are normally located. The facility is described in detail by Plate and Cermak.[25]

A less sophisticated (and less expensive) industrial aerodynamics wind tunnel (IAWT) designed by Cermak and modified as shown in Fig. 3b has proved to be very satisfactory for investigation of wind effects on buildings. Because of the somewhat limited length, artificial thickening of the boundary layer may be necessary to achieve the desired value of δ/H.

The simplest type of facility is the environmental wind tunnel (EWT) shown in Fig. 3c which was completed at Colorado State University in 1969. This facility has a test section 3.7 m wide by 2.4 m high with a flexible ceiling for pressure adjustment. The motivation for designing a tunnel with greater width of the working section was to permit more extensive building groups to be modeled without reduction of scale below 1:4000 or 1:5000. In this tunnel, with a limited test-section length of 17.4 m, some structural studies requires augmentation of the naturally developed boundary layer by means of vortex generators or other devices at the test-section entrance. Designation of the facilities shown on Figs. 3b and 3c as the IAWT and the EWT, respectively, is intended to facilitate identification rather than to indicate a particular functional feature. In fact, all three wind tunnels shown in Fig. 3 can be described according to their physical characteristics as low-speed, boundary-layer wind tunnels.

Development of boundary-layer simulation techniques for use with short test-section wind tunnels has received much attention during the last decade as indicated in the review by Peterka and Cermak.[26] Attempts to simulate the atmospheric boundary layer using short test-sections have included the use of graded grids, fences, vortex generators, jets, spires, and screens. The combination fence and vortex-generator system of Counihan,[27] the multiple-jet system of Teunissen,[28] the variable spacing horizontal slat system described by Cresci,[29] and the counter-jet system of Nagib et al.[30] are satisfactory systems if the surface roughness is adjusted properly. Surface roughness downstream from the stimulator must be equivalent to the roughness which, without the stimulator, would have produced an equilibrium boundary layer with the same characteristics as those generated by the stimulator.

III. Wind Forces on Buildings and Structures

Wind pressures on the exterior surfaces of buildings and structures vary both with time and location of the surface. The distribution and magnitude of these pressures are highly dependent upon geometry (adjacent buildings and local topography) and upon the meteorological variables. The latter variables include the mean wind-speed profile, turbulence scales and intensities, and direction of the mean wind. These variables are significant because they all affect separation, reattachment and, vortex formation on the surface (see Ref. 10, pp. 459-484 and Ref. 16, pp. 55-70). When natural winds are simulated as described in the previous section both the variables and their effects on wind pressures are accurately modeled, as confirmed through comparison of full-scale and model data for the Commerce Court Tower, Toronto, by Dalgliesh.[31]

Information related to wind pressures is currently being provided to structural engineers and architects for design purposes on more and more projects as buildings become more wind sensitive. This information includes mean forces and moments, local maximum pressure fluctuations, fluctuating forces and moments on the overall structure, fluctuating deflections, and accelerations. A rigid model is usually used to obtain mean forces and moments either through integration over the surfaces of mean pressures measured at many piezometer taps or directly by mounting the model on a six-component balance. The local maximum (peak) pressures required for curtain-wall design are also obtained from pressure measurements on a rigid model. All of the fluctuating quantities caused by instantaneous distribution of pressures over the exterior surfaces are usually obtained from measurement on a simplified aeroelastic model.

Wind-pressure data for buildings are being utilized in numerous applications other than in design of building frames and cladding. Such applications include design for natural ventilation; estimation of heat loss by infiltration; determination of effects on heating, air-conditioning, and ventilating systems; prediction of internal movement of smoke and gas caused by fires; and design of building entrance systems for safe operation during strong winds.

Rigid Model Investigations

A typical rigid model of a building is mounted on a turntable. As the model is rotated in 10-20 deg increments to change wind direction the model upwind of the turntable must be varied to simulate the upwind geometry of the city.

The instantaneous pressure differences are measured directly for simultaneous acquisition of both mean and fluctuation-pressure information with a system that has good

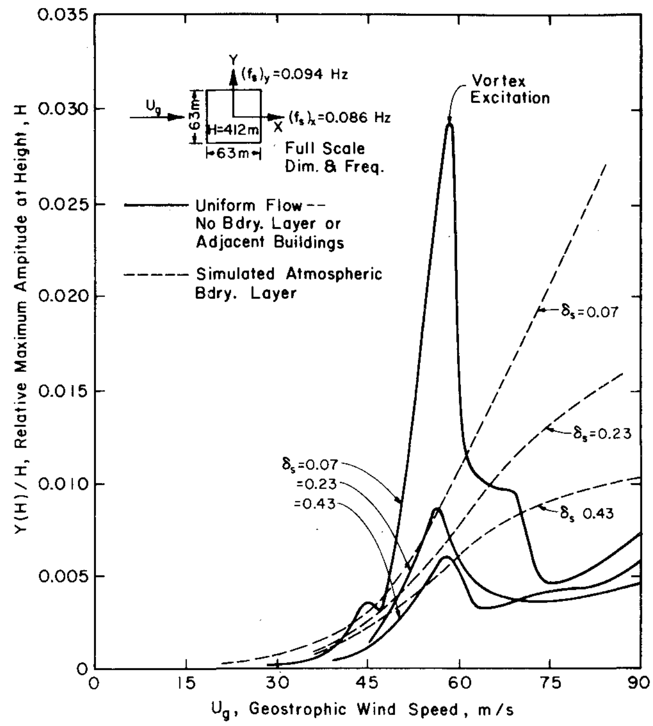


Fig. 6 Maximum lateral-deflection fluctuations for a single tower of the World Trade Center Towers, New York.[35]

frequency response up to 200 Hz and can measure and process the pressures at a large number of points quickly. A system designed at the Fluid Dynamics and Diffusion Laboratory (FDDL), Colorado State University, utilizes a 72-position pressure-tap selector switch mounted inside a model. Vinyl tubing (0.159-cm i.d., 30.5-cm length) connects the pressure taps sequentially to four Statham differential pressure transducers (Model PM 283TC). The reference pressure is ordinarily taken as the pressure measured by the side ports of a pitot-static tube located in the undisturbed flow directly above the model building.

Outputs of the four pressure transducers are simultaneously digitized and the pressure coefficients are computed on line and recorded as hard-copy printout. Pressure coefficients commonly in use are mean, rms of fluctuations from the mean, peak maximum, and peak minimum for a 16 s sample scaled with reference pressure corresponding to the freestream (or gradient) wind speed $\underline{\rho U_g^2}/2$. For example, the mean pressure coefficient is $C_{\bar{p}} = \overline{p - p_g}/0.5\rho U_g^2$ and the absolute peak pressure coefficient is $C_{\hat{p}} = |p - p_g|_{\max}/0.5\rho U_g^2$.

A convenient presentation of peak pressure fluctuation information for the curtain-wall designer is in the form of isobars plotted on building elevations. This can be achieved by a computer-plotter printout of contours based on the maximum absolute peak pressure measured at each pressure tap, irrespective of wind direction. An example of an absolute peak-pressure coefficient isobar plot for two faces of a rectangular building is shown in Fig. 4. Because of adjacent buildings, the isobars are not symmetrical. Results to date show that on upwind building faces and regions in which $-0.25 < C_{\bar{p}} < 0.25$, the pressure fluctuations follow a Gaussian distribution. However, in regions where $C_{\bar{p}} < -0.25$, regions where separation is followed by reattachment or where vortices contact the surface, the occurrence probability for large peak pressures greatly exceed values predicted from a Gaussian distribution.[32]

Aeroelastic Model Investigations

The instantaneous wind-pressure distribution on a building or structure results in forces and moments that vary with time. These forces and moments produce elastic deformations that have both random and periodic content. Measurement of the instantaneous pressure distributions is not practical because of their great variability over a building surface; therefore, deflections and acceleration of buildings and structures are obtained most easily and accurately by direct measurement on an aeroelastic model. The aeroelastic models used are usually simplified representations of full-scale elastic structures. Tall building and tower models reproduce motion corresponding to the primary sway modes and sometimes the primary torsional mode is included. Suspension bridge models are usually of the sectional type to reproduce primary vertical and torsional oscillations; however, more elaborate models are used to represent overall elastic behavior (see Ref. 9, pp. 518-558). Developments in aeroelastic modeling up to 1964 are presented by Scruton and Flint[33] and an account of more recent applications is given by Wardlaw and Cooper.[34]

Modeling Criteria

Criteria for achieving dynamic similarity are discussed in detail by Whitbread (Ref. 9, pp. 283-302). Convenient similarity parameters for motion of tall buildings and free-standing towers approximated by the fundamental sway modes are as follows:

Frequency ratio

$$\frac{f_{0X}}{f_{0Y}} = \frac{\text{natural frequency about } X \text{ axis}}{\text{natural frequency about } Y \text{ axis}} \tag{1}$$

Density ratio

$$\frac{\rho_s}{\rho_a} = \frac{\text{average mass density of structure}}{\text{mass density of air}} \tag{2}$$

Reduced velocity

$$\frac{U}{f_{0Y}w} = \frac{\text{mean velocity of wind}}{\text{reference velocity of oscillation}} \tag{3}$$

Logarithmic decrement

$$\delta_s = \frac{\text{energy dissipation/cycle}}{\text{total energy of oscillation}} \tag{4}$$

When the fundamental torsional mode is to be modeled an additional frequency ratio f_{0Z}/f_{0Y} must be added to these criteria. Here X and Y designate principal axes for the cross section at the building base and Z is the vertical axis passing through the mass center. Of course, in addition to the foregoing similarity criteria, the mass distribution and external geometry of the structure must be similar. When gravitational forces affect the motion of a structure, as in the case of suspension bridges, guyed towers, and cable-stayed pipeline crossings, another similarity parameter, gL/U^2, must be added. The criteria listed here are adequate for the simplest and most frequently used aeroelastic modeling for wind-engineering applications. More complex models that include higher modes of oscillation involve additional similarity parameters of the frequency-ratio type.

The dynamic response of a structure is related closely to wind characteristics; therefore, the similarity requirements for strong boundary-layer winds must be met also. Accordingly, the foregoing list of similarity requirements must be expanded to include equality of δ/H for model and prototype, $\partial p/\partial x \simeq 0$, and similarity of mean velocity and turbulence characteristic profiles at the site.

Applications to Buildings and Towers

A typical aeroelastic model arrangement for measurement of deflections and accelerations on a tall building or free-standing tower is represented schematically by Fig. 5. In the case illustrated no provision is made for torsional oscillation. The structural damping δ_s is usually not known with precision for the prototype building. Accordingly, the response is measured for several magnitudes of damping within the range of possible values (0.5-10% of critical damping). If only fluctuating forces and moments are of interest for determination of fatigue life on low, stiff buildings a rigid model mounted on a stiff strain-gaged support may be used. For this purpose, the support-model system must have a natural frequency in the range of 100-400 Hz in order to exceed the frequencies of force and moment fluctuations (Ref. 12, pp. 567-574 and Ref. 14, pp. 45-59).

The wind-excited motions of tall buildings, free-standing towers, and stacks are the result of three wind-structure interactions—buffeting, vortex excitation, and a galloping-type instability.[20,33] For low structures the primary mechanism is a buffeting action by gusts. Structures of medium height and moderate structural damping experience excitation by buffeting and vortex shedding. Tall structures with moderate to light damping may be excited by simultaneous action of buffeting, vortex shedding, and a galloping-type instability.

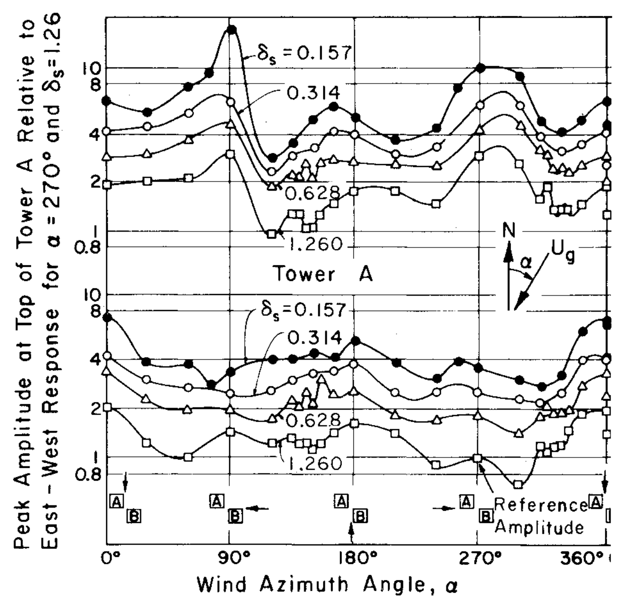


Fig. 7 Peak response for 1:500 scale model of Tower A of World Trade Center Towers, New York, for a gradient wind speed of 50 m/s over southeast portion of the city—unpublished report of Skilling, Helle, and Christiansen and Robertson, New York, 1966.

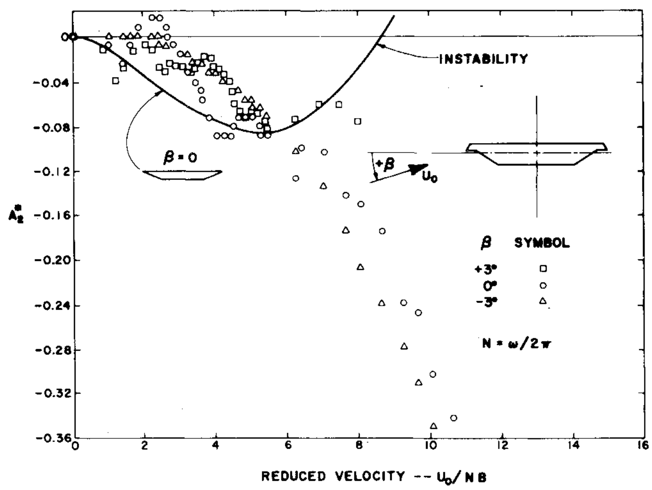


Fig. 8 Dimensionless torsional-stability aerodynamics coefficient A_2^* for Ruck-a-Chucky suspension bridge.[38]

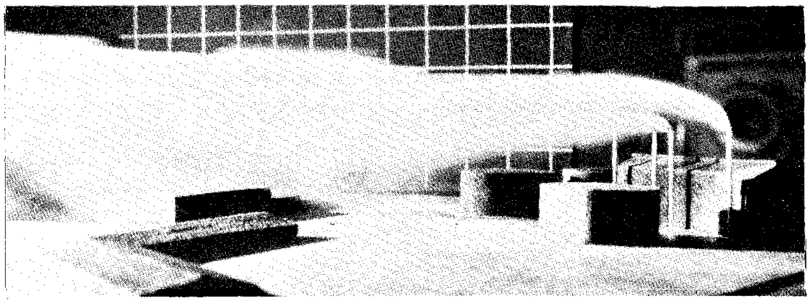


Fig. 9 Downwash of plumes emitted from 30.5-m stacks of 1:200 scale model of power plant on the island of Maui, H.I.

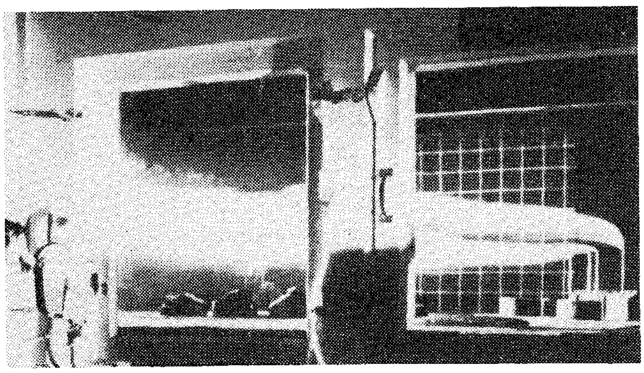


Fig. 10 Plumes emitted from 68.6-m stacks of Maui power plant show elimination of downwash.

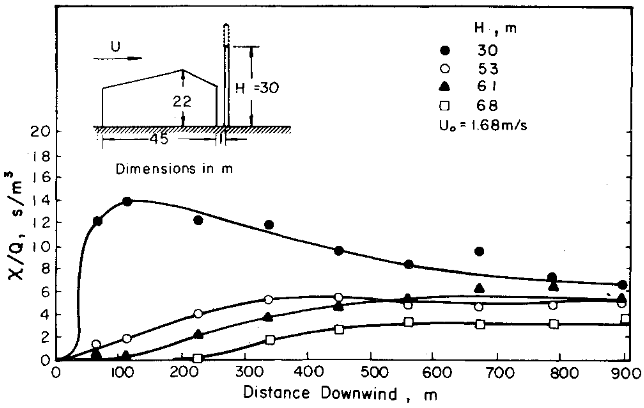


Fig. 11 Effect of stack height H on ground-level concentration χ/Q in downwash region.

In the United States the first detailed aeroelastic model study made on a tall building to obtain data for design purposes was for the World Trade Center Towers, New York. This study provides an instructive application of wind tunnels to wind engineering. A 1:500 scale aeroelastic model was subjected to simulated atmospheric boundary-layer flow in the meteorological wind tunnel (Fig. 3a). In a companion study at the National Physical Laboratory at 1:400 scale model of one tower was studied by Whitbread and Scruton.[35] Peak lateral deflections of the tower top were measured for two types of flow, uniform flow (no boundary layer) and a simulated atmospheric boundary-layer flow. Figure 6 gives these results for wind normal to one face as a function of wind speed and structural damping. In uniform flow the response is dominated by vortex excitation at a wind speed of 55 m/s when the vortex shedding frequency is equal to the natural frequency $(f_s)_Y$ of the building. The vortex-excited resonant response disappears for the simulated atmospheric boundary-layer flow. However, as the simulated natural wind speed increases, the response amplitudes increase as a result of strong buffeting and galloping for the lightly damped case. These results emphasize the necessity of modeling dynamic effects resulting from wind loading on structures in a properly simulated atmospheric flow.

Response of Tower A to a gradient wind U_g of 50 m/s with both towers present is given in Fig. 7. The peak amplitude is given for the north-south and east-west response as a function of wind direction relative to the tower configuration and damping. To obtain the changes of wind direction the two towers were rotated while the surrounding city model was maintained in a position. These data indicate a strong interactive effect from Tower B. Generally, the peak amplitudes for cross-wind motion are substantially greater than for the along-wind direction.

Davenport et al.[36] used a seven-mass system with 24 degrees-of-freedom to study dynamic response of the Sears Tower, Chicago. The primary deflection response was found to be for the fundamental sway mode. The most significant difference was a 15% increase in spectral energy for acceleration at the building top. These results give further justification for the use of simple fundamental sway-mode models for determination of dynamic response for design of tall buildings and structures.

Data of the form illustrated by Fig. 7 can be combined with local climatological data as described by Davenport[37] to determine the probability that deflections, stresses, and accelerations of specified magnitudes will be exceeded.

Applications to Suspension Bridges

Since 1940, with the collapse of the Tacoma Narrows suspension bridge resulting from wind-excited torsional oscillation, wind tunnel investigations have been used to assure an aerodynamically stable design as well as to obtain mean drag, lift, and moment coefficients. Two types of models are in common use, sectional models and full models. The modeling criteria and a description of numerous examples are presented by Vincent and Walshe (Ref. 9, pp. 488-515 and 518-558, respectively).

Sectional models are designed as two-degree-of-freedom models to simulate vertical and torsional motions at the lowest fundamental frequencies. In an effort to maximize the Reynolds number, models have traditionally been constructed to the largest scale feasible (1:25-1:50) that will permit a length-to-width ratio large enough to develop a flow over the model that is effectively two-dimensional. Consequently, the models are too large for study in a simulated atmospheric boundary layer. The result is that all such models have been subjected to low-turbulence flow of uniform mean velocity. A 1:40 scale model of this type for the proposed Ruck-a-Chucky Bridge across the American River in California was studied in the industrial aerodynamics wind tunnel (FDDL).

Torsional stability of the deck is very sensitive to geometrical features that affect separation and reattachment of flow. In particular, the leading-edge geometry is critical. Figure 8 compares the torsional-stability aerodynamic coefficient A_2^* for an unstable shape with the stable shape selected for the Ruck-a-Chucky Bridge as a function of the reduced velocity.[38] The coefficient A_2^* enters into the equation of motion for the torsional mode as a multiplier of the angular velocity to produce an aerodynamic self-excitation

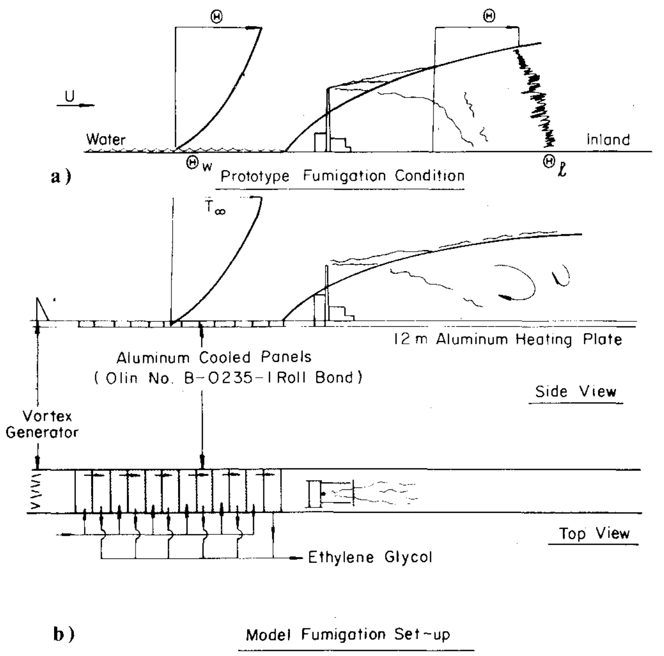


Fig. 12 Schematic representation of a) thermally stratified boundary layer for onshore breeze resulting in fumigation and b) arrangement for modeling in meteorological wind tunnel fo the FDDL.

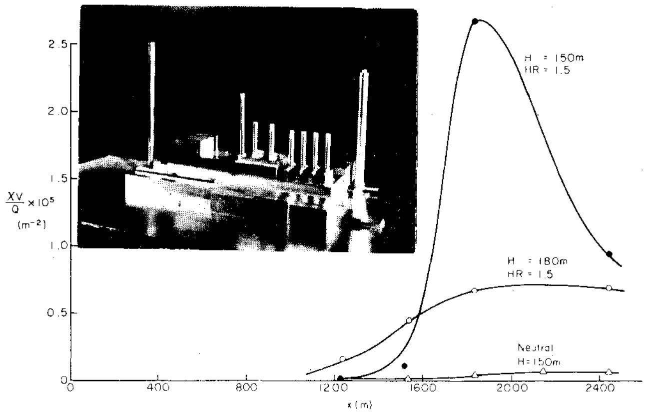


Fig. 13 Ground-level concentrations downwind of 1:400 scale model of shoreline power plant, neutral flow and a model sea breeze.

moment.[39] Section-model investigations in a nonturbulent airstream are open to criticism since turbulence of integral scales equal to and larger than the deck width may affect separation and reattachment sufficiently to modify the stability. An effort is currently in progress in the FDDL at Colorado State University to design and construct a large-scale gust generator that can be used to resolve this uncertainty.

Full models of suspension bridges have been used for several investigations of aeroelastic behavior. These include the crossings of the Tacoma Narrows,[40] the Firth of Forth and River Severn[41] and the Lions' Gate Bridge over Burnard Inlet, Vancouver.[42] These aeroelastic models of the entire bridge including deck, cables, hangers, and towers are not only very expensive but, because of their small scale, raise questions regarding Reynolds number effects unless a very wide wind tunnel test section is provided. A 1:100 scale model of the Severn Bridge was studied in a wind tunnel at the National Physical Laboratory, England, constructed especially for this purpose. The test section is 2.1 m high, 18.8 m wide and 18.3 m long. A special wind tunnel consisting of a jet 1.8 m high and 16.0 m long enclosed in a working chamber constructed by the Department of Civil Engineering at the University of Tokyo for investigation of wind action on suspension bridges is described by Hirai et al.[43]

IV. Mass Transport by Wind

Physical modeling of mass transport in wind tunnels capable of simulating the atmospheric boundary layer has become an important source of data for treatment of many air-pollution and safety problems. Determination of concentrations of SO_2, radioactive gases, and H_2S from fossil fuel, nuclear, and geothermal power plants; CO, hydrocarbons, and NO_x from parking garages and dense traffic; methane from liquid natural gas (LNG) spills; and toxic fumes from chemical spills are the most common cases involving the dispersion of gases. The transport of solids is encountered in dispersion of silver iodide over complex terrain for cloud seeding, snow drifting and soil and sand movement. When the boundary geometry is complex (composed of buildings, trees, uneven terrain) the uncertainty of concentrations calculated from the numerical or mathematical dispersion models for small distances from the source becomes very large. These are the conditions for which dispersion modeling in wind tunnels is the most accurate and achievable.[1,44] Several examples of mass transport problems that have been studied by physical modeling in wind tunnels will be described to illustrate the methods used.

Transport of Gases

Physical modeling of gas transport imposes certain similarity requirements for the source fluid in addition to those required for simulation of the natural wind. One of the most essential similarity parameters is the ratio of emission speed for the gas to wind speed at the vent or stack height H: V_s/U_H. The other essential parameter has the form of a Froude number for the emitted gas: $\rho_a U_H^2[(\rho_a - \rho_s)gD]$. An additional consideration is the Reynolds number for source gas flow through the stack or duct to a vent. The effective Reynolds number for this internal flow should be made as near the prototype value as possible by roughening the internal surface.

One of the most common problems associated with gaseous exhausts from power and other industrial plants is downwash. The problem may occur for an existing plant where stacks are too low or exit velocity too small. On the other hand downwash must be avoided by proper design for proposed plants. In both cases, data on plume behavior are needed to select a minimum stack height with reasonable gas exit velocities that will insure downwash-free operation. This is a short-range dispersion problem that is most pronounced for strong winds; therefore, it can be treated effectively by physical modeling in a wind tunnel boundary layer with neutral thermal stratification. A problem of this nature was encountered at a power plant on the island of Maui, H.I. The wind tunnel investigation was made by Cermak and Nayak[45] using the meteorological wind tunnel (FDDL) and a 1:200 scale model. The existing problem with stacks of only 30.5 m height is illustrated by injecting smoke into the model stacks as shown by Fig. 9. Model Froude number equality with the prototype Froude number for hot stack gases was obtained by adding helium to the modeled emissions. The position of the plume after raising the stacks to a height of 68.6 m is shown in Fig. 10. A stack height of 68.6 m was determined to be the minimum height necessary to avoid exceeding allowable minimum ground-level concentrations. This was accomplished by introduction of a known concentration of tracer gas (krypton-85) into the stack gas and taking samples at ground level downwind of the model by means of an array of sampling ports in the wind tunnel floor. The variation of maximum ground-level concentrations with stack height obtained by this technique is shown in Fig. 11.

An interesting application of the meteorological wind tunnel is the problem of fumigation by elevated plumes that

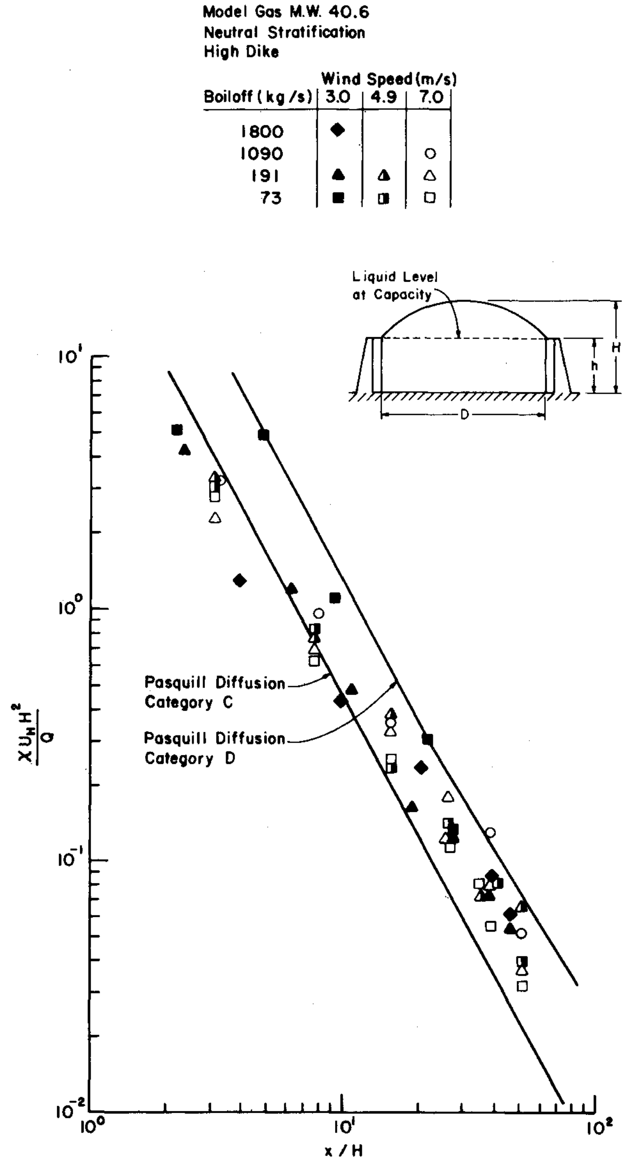
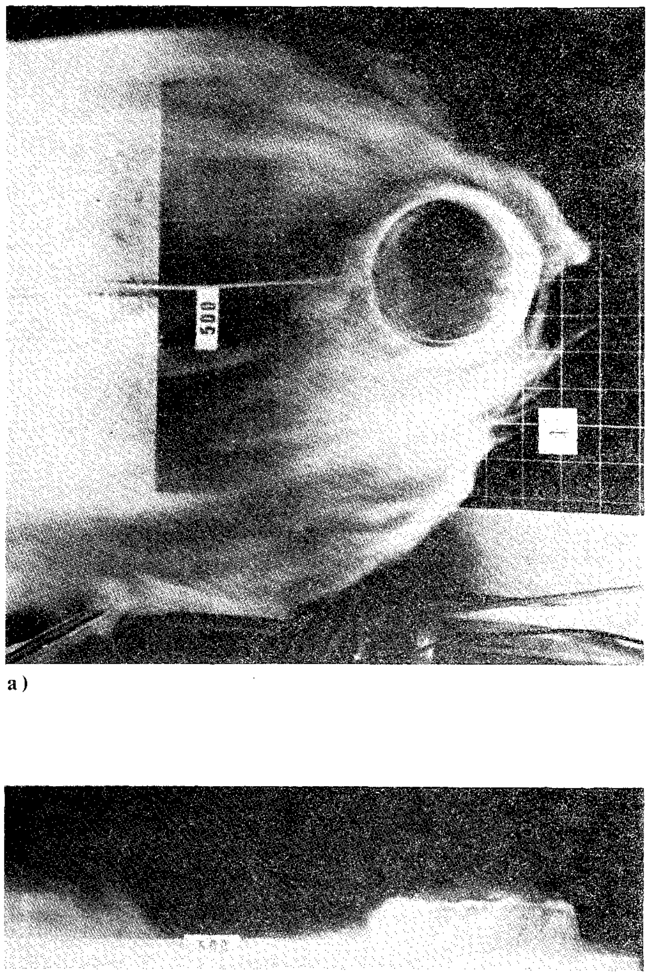


Fig. 14 Maximum ground-level concentration downwind of LNG release from tank surrounded by a high dike measured in meteorological wind tunnel (FDDL) for a 1:200 scale model.[47]

cause high ground-level concentrations when stability of the atmosphere is destroyed by heating from below.[46] This condition occurs frequently for powerplants located on shorelines of large bodies of water during onshore breezes. When these winds with stable thermal stratification flow onto warm land as shown in Fig. 12 an unstable internal boundary layer grows in depth until it reaches plume height. The problem for a given powerplant is to predict the distance downwind to fumigation and the ground-level concentration that will result. Physical modeling of this phenomenon introduces an additional similarity parameter to characterize the surface temperature discontinuity. A convenient dimensionless parameter is the heating ratio

$$HR = \frac{(T_{\text{land surface}} - T_{\text{water surface}})}{\Delta x} \frac{\Delta z}{(T_{\Delta z} - T_{\text{water surface}})}$$

This parameter for the model should be made equal to the prototype value where the temperature T is replaced by the potential temperature θ. Limited data for shorelines along the Great Lakes indicate that HR has values of from 1.3 to 1.8. Figures 12 illustrates the boundary heating and cooling arrangement for physical modeling of the fumigation phenomenon. Typical results obtained from the measurement of tracer gas concentrations are shown in Fig. 13.

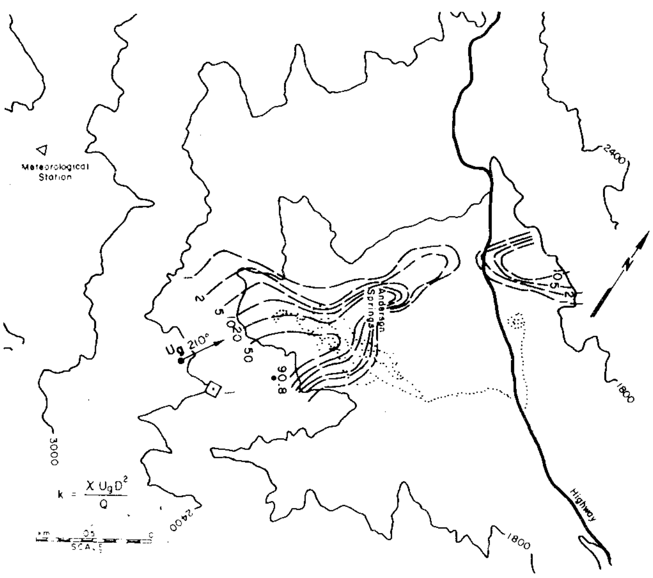


a)

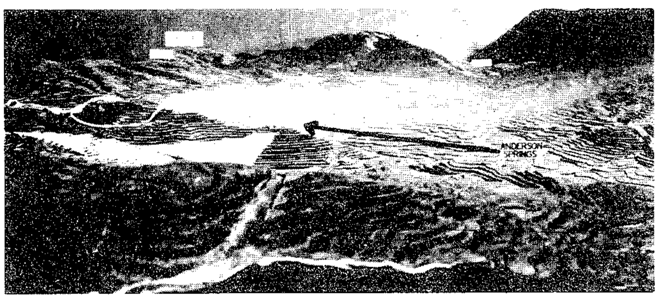
b)

Fig. 15 Flow of simulated cold methane gas over high-dike surrounding LNG storage tank, 1:200 scale model.

Dispersion of methane downwind of a ruptured LNG tank has been modeled in the meteorological wind tunnel by Neff et al.[47] The most common configuration of an LNG storage facility is a circular tank surrounded by a high dike as shown in Fig. 14. When LNG is released into the annular space boiling occurs and cold methane flows over the dike as a dense gas. Conservative values of concentration downwind for safety evaluation purposes were obtained by using a mixture of freon and nitrogen at room temperature to simulate the dense source gas. In this case the velocity ratio V_s/U_H for stack gas emissions is replaced by a momentum ratio $\rho_g Q^2/(\rho_a U_H^2 H^4)$ where the volumetric rate of source-gas flow is obtained from boiloff rates estimated with the help of field experiments. The maximum mean ground-level concentrations downwind from the tank are shown for a set of boiloff rates and wind speeds in a neutral atmosphere for Fig. 14. As can be seen from flow visualization of the dense gas motion in Fig. 15, an uncoupled two-fluid system is formed initially that gradually merges as mixing takes place. The modeling is being extended to include the effects of heat transfer to the cold plume and unsteadiness of source strength by using a mixture of helium and nitrogen at a temperature of $-260°$F as the source gas with a programmed release rate.[47]



a) Isopleths of nondimensional concentration coefficient k(× 10^5).

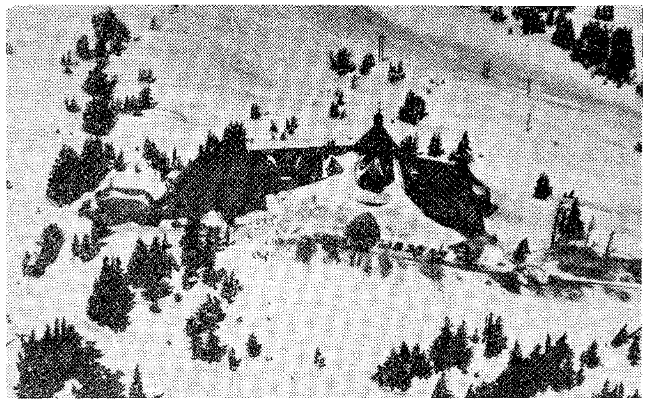


b) Flow visualization

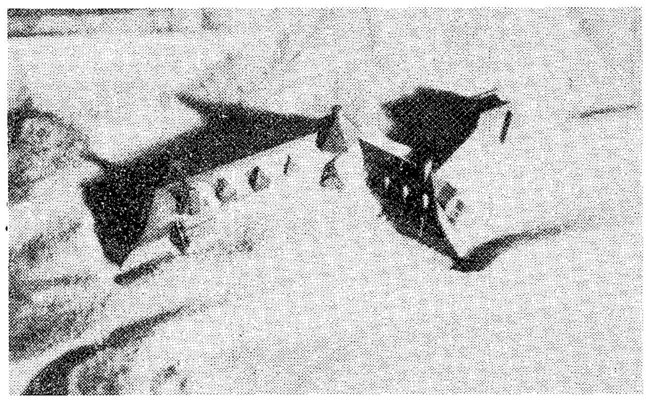
Fig. 16 Dispersion over 1:1920 scale model of Geyser Field, Calif., in environmental wind tunnel, FDDL, (Unit 16, Site 1, wind direction 210°, wind speed 9.8 m/s).

Another important application of physical modeling is determination of flow and dispersion over complex terrain. Small-scale models—1:2000 to 1:20,000—are required for this application because of the need to model large areas and the limited width of the wind tunnels (2-4 m) available for this purpose. For these studies particular attention must be given to surface roughness of the model in an effort to meet the criterion defined in Fig. 1. Examples of this type of modeling at Colorado State University include dispersion of toxic gases over the former Pacific Missile Range at Point Arguello, Calif.,[19] dispersion of cloud seedinag materials over the Rocky Mountains in Colo.,[48] dispersion of SO_2 from the Kahe Power Plant, Oahu, H.I., and H_2S over the Geyser Field, Calif.[49]

Dispersion over the Geyser Field[49] provides a good illustration of physical modeling over complex topography. This study used a 1:1920 scale model in the environmental wind tunnel (FDDL). Mean ground-level concentrations were measured for neutral flows from three wind directions (210°, 230°, and 250° azimuth) and three prototype mean wind speeds of 3.2, 6.5, and 9.8 m/s at the meteorological station 10 m above the gound. The corresponding model wind speeds to preserve Froude-number equality for the source emissions was 0.2, 0.4, and 0.6 m/s. Isopleths of the nondimensional concentration coefficient $K = \chi U_g D^2 / Q \times 10^5$ are shown in Fig. 16 for a 9.8 m/s wind from 210° azimuth.



a) Timberline Lodge on Mt. Hood, Washington



b) Model of Timberline Lodge (1:384 scale)

Fig. 17 Snowdrift geometry for full-scale and small-scale model of Timberline Lodge in the meteorological wind tunnel, FDDL.

Transport of Solids

Studies for sand movement by Bagnold[50] in 1935 mark the first attempt to physically model the transport of solid particles by wind. Erosion of soil during the "dustbowl" period of the 1930's stimulated research on the mechanics of wind-soil interactions and led to development of a portable wind tunnel by Chepil and Milne.[51] This facility had a 1.22-m-wide, 1.08-m-high, and 8.54-m-long working section and could be transported into the field and placed on the ground which then constituted the lower wind tunnel boundary. Gerdel and Strom[52] and Strom et al.[53] have investigated the requirements for physical modeling of blowing snow and used a wind tunnel to study snow drifting. Recently Iverson et al.[54] have applied wind tunnel modeling techniques to an investigation of Martian crater-wake streaks. Similarity parameters, using the most accessible variables, significant for a phenomenon such as snow drifting, are u_f / U_H, d_p / H, $U_H^2 / (g d_p)$, and e in addition to parameters needed for similarity of the atmospheric-boundary-layer winds. Here u_f is the terminal speed of a particle in free fall, d_p is the particle diameter, and U_H is the mean wind speed at height H.

Wind tunnels are being used more and more frequently to investigate snow-drifting characteristics around a building complex during the planning stage of a new development.[55] Data on potential drift locations can be used to modify the relative location of buildings or the shape of a particular building to eliminate or reduce the collection efficiency at a particularly troublesome location. A study of this nature is underway in the meteorological wind tunnel to provide information for the location and shape of an expansion at the Timberline Lodge on Mt. Hood. The model building and topography are constructed to a scale of 1:384 and pulverized styrofoam is being used to simulate snow. Figure 17 is a photograph of the existing lodge with typical snow drifts developed by the prevailing west wind. A photograph of the model is shown in Fig. 17 for the same meteorological conditions to illustrate the similarity between modeled and actual snow-drift geometry.

V. Local Features of the Wind

Wind tunnels such as those shown in Fig. 3, because of their capability to simulate wind in the atmospheric boundary layer, can be used to determine wind characteristics near elements of complex boundary geometry. Thus the details of wind structure near buildings, in urban complexes, in forests, and over complex topography, as implied in the previous sections of this paper, can be measured and observed by flow visualization. This capability of removing the uncertainty of wind behavior has a host of important applications.

Historical wind-variable data obtained at established meteorological stations can be used to establish wind characteristics at nearby locations where no historical data exist. Through measurements over a model that include the station for which records are available, correlation functions can be developed that transform the available wind-variable statistics into statistics for any location of interest contained on the model. This technique has been used to translate wind data collected by the U.S. Weather Service at the Federal Building of downtown San Francisco to the Yerba Buena Center,[56] from the Toronto airport to downtown Toronto (Ref. 15, pp. 109-143), and from a single meteorological station in the Geyser Field[49] shown in Fig. 16 to the location of proposed geothermal power plants. The same approach can be used to extend available wind data for the purpose of developing wind intensity zones in a city for specification of wind-load requirements. Division of a city into natural subregions in this manner has been termed microzonation by Lew and Hart.[57] They have established an initial wind microzonation for Los Angeles from data available at existing meteorological stations.

The wind environment in plaza areas at the foot of tall buildings, in passageways through buildings at street level, in apartment buildings with open ventilation, in sports stadia, and in recreation areas within large urban centers can be determined in fine detail through use of small-scale models. Among studies of this nature are those described by Isyumov and Davenport (Ref. 12, pp. 403-421) for city plazas, by Melbourne and Joubert (Ref. 11, pp. 105-114) for winds at the base of tall buildings, by Cermak and associates for the Yerba Buena Center[56] and the Candlestick Ballpark,[58] and by Peterka and Cermak[59] for the University of Pennsylvania Hospital. Modification or addition of architectural details, optimum location of buildings relative to other buildings or topographic features, and the locations for plantings of trees and shrubs to alleviate the buffeting of people by wind result from such investigations. Through wind tunnel experiments using people as test subjects Hunt et al.[60] have developed tentative criteria for relating wind characteristics to performance ability and equilibrium while walking.

Determination of wind characteristics over buildings used as ports for helicopters, VTOL, or STOL aircraft is an important step in the evaluation of flight safety. Using a 1:300 scale model in the environmental wind tunnel (Fig. 3b) Peterka and Cermak[61] measured mean wind direction and turbulence intensity for flight paths over an elevated STOLport. Many accidents involving small aircraft during landing or takeoff have been ascribed to adverse and unexpected wind disturbances created by the wake of buildings near the edges of runways. Extensive measurements of wake characteristics for several building shapes modeled in the meteorological wind tunnel (Fig. 3) have been made and reported by Woo et al.[62] These data include mean velocities; turbulence intensities; vertical, lateral, and longitudinal space correlations, and spectra for distances up to 30 H downwind of the building. These data can be used to estimate the degree of hazard to small aircraft resulting from existing buildings near runways or to determine how far new buildings should be located from a runway without exceeding an acceptable hazard frequency of specified magnitude. Mean velocity and turbulence characteristics are being measured over a family of two-dimensional ridges that are being modeled in the meteorological wind tunnel.[63] A data set encompassing systematic variation of meteorological and geometrical variables is being developed to assist in the evaluation of sites for wind-power installations.

VI. Summary

Extreme complexity of boundary conditions where wind interacts with people, buildings, vegetation, and topographic features results in flowfields that defy description by numerical or analytical methods. Our inability to describe these natural flows has required extensive reliance on physical modeling to obtain data for treatment of problems associated with local heat, mass, and momentum transport by wind in the atmospheric surface layer (wind-engineering problems). Physical modeling in wind tunnels designed to simulate natural winds can yield reliable data to help solve wind-engineering problems of the types identified in this paper. When these data are combined with local climatological and meteorological data statistical predictions can be formulated for use in development of designs and plans based on probability-of-exceedance criteria.

Through research in which geometrical and meteorological variables are systematically varied, wind-effect data can be measured in wind tunnels to establish the range of magnitudes of specific dependent variables for simple reference configurations. Information of this type can be used to develop design criteria that would reduce the need of wind tunnel studies for each specific development. Systematic studies of this nature for a family of building shapes to determine wind forces, moments, peak pressures, building-building interactions and dynamic response supported by the National Science Foundation are now in progress in the Fluid Dynamics and Diffusion Laboratory.

Acknowledgment

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