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Applications of Fluid Mechanics to Wind Engineering—A Freeman Scholar Lecture

J. E. CERMAK

Professor-in-Charge,
Fluid Mechanics Program
and Director, Fluid Dynamics
and Diffusion Laboratory,
Colorado State University,
Fort Collins, Colo. Mem. ASME

Wind has always had a strong influence, both unfavorable and favorable, upon man and his activities. Within the last decade needs for treatment of wind effects from an engineering point-of-view have increased tremendously. Losses due to wind ($500,000,000 in property damage, 240 deaths and 2600 injuries annually), increased demand and concern for human comfort, serious attempts to control air pollution, and the development and expansion of energy-production capabilities have resulted in applications of engineering to problems for which a body of knowledge has only started to emerge in the United States. The primary elements of this body of knowledge are found in the disciplines of meteorology, fluid mechanics, aerodynamics, and structural mechanics—organizing this knowledge to form a coherent subject-matter base for wind engineering is a real challenge for fluids engineers.

The objectives of this review are to establish an initial subject-matter base for wind engineering, to demonstrate current capabilities and deficiencies of this base for an engineering treatment of wind-effect problems, and to indicate areas of research needed to broaden and strengthen the subject-matter base. Focusing of subject matter for wind engineering is accomplished through a historical summary of relevant scientific and technological material, an examination of information on wind characteristics, and a review of current capabilities for physical modeling of winds and wind effects in the laboratory. Current methods and capabilities in wind engineering are demonstrated by a review of problems related to atmospheric advection and dispersion of air pollutants, wind forces on buildings and structures, and control of winds. Research needs are specified separately for each area reviewed—wind characteristics, simulation of the wind, atmospheric transport of air pollutants, wind forces, and wind control.

Physical modeling of boundary-layer-type winds and wind effects by measurements on small-scale models placed in long-test-section, meteorological wind tunnels currently provides the most reliable source of data for wind engineering. Coordinated measurements on full-scale systems and their small-scale models are necessary for continued confirmation of similarity for the laboratory data and for development of new modeling capabilities. In particular, development of a tornado simulator is an urgent need to support structural design for nuclear-power-plant facilities.

Intensive analytical investigations of three-dimensional, thermally-stratified, turbulent boundary layers; separation of turbulent, unsteady flows; turbulent shear flow over bluff bodies; and interacting turbulent flows with a variety of turbulence characteristics are needed to ensure future progress in wind engineering. These investigations are needed to provide a framework for correlation of both laboratory and full-scale data, to support efforts to develop numerical modeling as a practical tool, and to develop a better understanding of the physical processes involved. These flow problems represent formidable frontiers of turbulent fluid motion. Therefore, investigations in the fluid-mechanics laboratory coupled with measurements on full-scale systems are expected to be the primary sources of information for wind engineering in the immediate future.

1 Introduction

Wind engineering is best described as the rational treatment of interactions between wind in the atmospheric boundary layer and man and his works on the surface of Earth. A rational treatment of wind effects has been made possible by a synthesis of knowledge from the traditional fields of fluid mechanics, meteorology, mechanics of structures, and physiology to form a new discipline. Although aerodynamics is of central importance in this new discipline, applications are for the most part nonaeronautical in nature. Atmospheric transport of air pollutants, wind effects on buildings and structures, and modification of wind in urban areas by buildings, structures and streets are important examples of interactions with which the wind engineer must work. The wind engineer's task is not only to minimize loss of life and damage to property which result from adverse wind effects but also to maximize human comfort and economy of design by utilization of beneficial wind effects. If attention is focused on rivers of air rather than rivers of water, wind engineering may be described as a field of engineering similar to hydraulic engineering, a well-known discipline richly endowed by John Ripley Freeman [1][1] to whose engineering genius this lecture is dedicated.

Several factors have contributed during the last decade to an intensification of concern about wind effects and an acceleration of efforts to minimize damage to property and injury or discomfort to people while attempting to maximize the pollution-dilution capabilities of the atmosphere. The direct economic loss resulting from damages caused by hurricanes, tornadoes and

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[1] Numbers in brackets designate References at end of paper.

other severe windstorms in the United States is a major factor. The Office of Emergency Preparedness [2] has reported that the average annual loss resulting from windstorms during the last 50 years is approximately $100,000,000. However, during the last decade the annual windstorm damage has exceeded $500,000,000 annually for six of the years! Within the period 1963–1970, Sanders [3] has estimated that windstorms accompanied by all other meteorological phenomena have caused 1,677 deaths and 18,285 injuries.

Loss statistics of this type are expected to increase in magnitude because the percentage of land area occupied by people and structures continues to increase; the use of new structural designs and materials result in structures and buildings which are light in weight, are tall or are of large areal extent and have low mechanical damping; glass is used to form large surfaces on buildings and mobile homes are being produced in ever-increasing numbers. These trends have stimulated efforts to describe wind characteristics, to understand the nature of flow over bluff bodies, and to develop adequate design procedures which will not only result in very low probabilities for catastrophic failure but will yield acceptably low probabilities for localized damage.

Another important factor stimulating the development of wind engineering is the increased attention being given by architects, city planners and engineers to the matter of *human comfort* in the use of their works. Considerations of this nature have resulted in much concern about wind-excited accelerations of tall buildings and towers, wind-generated noise, buffeting of pedestrians by gusty winds at street level, entrainment of soil and other solid debris, and snow drifting.

The urgent need to control air-pollutant concentrations and thus *protect the environment* is a factor which has caused renewed interest in the transport characteristics of wind. Major pollutant sources are industrial-plant stacks and automotive vehicles. Stack height, stack location relative to plant buildings and to topographic features, stack location relative to population centers, location of traffic arteries within an urban complex and location of vehicle parking facilities which will enable minimal pollutant-concentration standards to be met an acceptable percentage of the time, are matters of real concern.

The necessity to *develop new energy sources* is a recently recognized factor which has accelerated the search for more knowledge on wind characteristics and topographic effects. Wind forces on nuclear power-plant structures created by tornadoes, flight characteristics of tornado-generated missiles (objects placed in flight by the tornado), wind forces and heat-transfer rates on large solar-energy collector surfaces, and wind characteristics at potential wind-power sites are subjects which must be considered and developed.

As indicated by the foregoing comments, wind engineering is indeed a discipline which ranges broadly in basic subject matter and in application. However, as in hydraulic engineering, the foundations of wind engineering are comprised of the fundamental elements of fluid mechanics. The objective of this review is to demonstrate that through the use of established concepts and principles of fluid mechanics, a coherent foundation for wind engineering is emerging. Accordingly, emphasis will be placed on integrating fluid-dynamical knowledge of turbulent boundary layers, turbulence and turbulent diffusion, with knowledge on motion of the lower 300 m (1000 ft) of the atmosphere. The purpose of such a unified framework is to provide a natural medium for both quantitative and qualitative descriptions of wind effects which can be used for engineering design and analysis.

Most of the applications encountered in wind engineering are local in nature, i.e., the region or object concerned extends over distances of only several miles or less. This implies that scales of atmospheric motion corresponding to microscale and small-scale turbulence (length scales in the ranges 10^{-3} to 10^1 m and 10^1 to 10^4 m, respectively) are of primary significance for determining the character of mass transport and wind forces on buildings—two wind effects of major practical importance. However, these scales of motion are affected in turn by mesoscale motions (10^4 to 10^5 m) which are caused by complex topography, nonuniform heating of Earth's surface, and rotation of Earth.

Accordingly, the atmospheric motions of importance in wind engineering are affected strongly by the complex boundary conditions associated with specific sites—nonuniform temperature distributions, nonuniform roughness with element heights equal to or in excess of the atmospheric surface-layer depth, nonplanar topography and a variety of local climatological factors. The resulting natural-wind characteristics often deviate strongly from those associated with conventional two-dimensional boundary layers. The mean motion may be three dimensional and the

Nomenclature

B_T = dimensionless coefficient
B_U = dimensionless coefficient
C_p = specific heat at constant pressure
$C_{\bar{p}}$ = local mean pressure coefficient
C_p' = local peak pressure fluctuation coefficient
C_{prms} = local rms pressure coefficient
E_u, E_w = energy spectrum of longitudinal and vertical velocity fluctuations, respectively
f = Coriolis parameter
g = gravitational acceleration
H_0 = surface heat flux
H_s = effective stack height
k = thermal conductivity
k' = Kármán constant
K_M = turbulent eddy viscosity
L = Monin-Obukhov length
L_e = length of upwind fetch
L_x = integral scale for longitudinal component of turbulence
P = local static pressure
Q = source strength
r = radial coordinate
$S_u(\omega)$ = energy spectrum of longitudinal velocity fluctuations
t = time
T = local instantaneous temperature
T_* = friction temperature
ΔT = temperature difference (departure from adiabatic lapse rate)
u_i' (u', v', w') = ith component of velocity fluctuation
u_i = local ith component of instantaneous velocity
u_* = friction velocity
U, V = horizontal components of local mean velocity
U_i = ith component of local mean velocity
x_i = ith space coordinate
z_0 = roughness length
δ = boundary-layer thickness
δ_{ij} = Kronecker delta
δ_s = logarithmic decrement of structural damping
ϵ = energy dissipation rate per unit of mass
θ' = local potential temperature fluctuation
κ = wave number
ν = kinematic viscosity
ρ = mass density
σ_y, σ_z = standard deviations of particle space distribution
τ_0 = surface shear stress
ϕ = dissipation function
χ = concentration
ω = frequency
Ω_i = ith component of angular velocity
$< >$ = ensemble average

Subscript

$(\ )_0$ = reference quantity
$(\ )_g$ = value of quantity at the geostrophic wind height

Superscript

$(\ )^*$ = nondimensional quantity

turbulence structure may be nonhomogeneous in planes parallel to the surface. Because of this strong nonlinear interaction between atmospheric motion and the objects over which flow takes place, engineers have learned to rely more heavily on physical modeling and similarity analysis [4, 5] than on direct mathematical analysis for a quantitative description of wind effects. Today the fluid mechanics laboratory is as indispensable to the wind engineer as its has been to the hydraulic engineer for the past century [1]. Accordingly, much of this review is devoted to the fluid mechanics of natural-wind simulation and the utilization of simulated winds to determine wind effects for engineering purposes.

The broad objective of this review is to present a perspective of wind engineering which will stimulate further development of this field of importance to the national welfare by fluids engineers, aerodynamicists and meteorologists. Efforts to attain the objective are concentrated on an attempt to achieve the following:

(*a*) focus past and contemporary scientific and technological subject matter to form a subject-matter base for wind engineering,
(*b*) demonstrate what can and cannot be done currently with the subject-matter base to help in the solution of engineering problems, and
(*c*) indicate important unresolved problem areas which need to be illuminated through further research.

2 Historical Summary

In the introductory statement an attempt was made to identify some needs of modern society which require an accelerated development of the science and practice of wind engineering. This historical sketch endeavors to trace the evolution of the several areas of knowledge which have converged to form the field of wind engineering as it exists at this time. The following areas are of particular significance: fluid-dynamical description of natural winds, fluid-dynamical description of wind forces on objects, mass transport, atmospheric modeling techniques, and the development of laboratory facilities for simulation of the atmospheric boundary layer. Only the highlights of developments in these areas will be mentioned since it is neither the purpose of this paper nor the intention of the writer to present a comprehensive historical review. This is perhaps a treacherous course since the identification of highlights will be influenced by the writer's research and his other activities related to wind engineering. Accordingly, apologies are extended to all who have made noteworthy contributions but are not noted here because of either the limited scope of this account or the peculiar perspective of the writer.

Prior to 1700. Man and his activities have always been affected by wind. Strong winds were thought to emerge from evil sources and were, and still are, feared because of their capability for destruction. Accordingly, it is understandable that the first recorded intellectual efforts of substantial substance related to wind engineering were on the nature of wind itself. Aristotle (384–322 BC) produced a book entitled *Meteorologia*, and Theophrastus of Eresus (371–286 BC) wrote a book *On Winds and Weather Signs* [6]. Although these writings were rooted in mysticism and provided little of practical value to aid man in his battle against wind they stimulated much thought during the next sixteen centuries about the true nature of wind. Motivated by growing needs to describe movement of air in the atmosphere and water in the rivers, a physical description of fluid motion began to emerge.

The works of Leonardo da Vinci (1425–1519) [7] mark the beginning of scientific expression in the description of natural phenomena. As a mathematician, natural philosopher, and engineer his work exemplifies the integration of abstract concepts, understanding of natural phenomena, and application to man's needs which are essential for a wind engineer. Among his many contributions are the expression for continuity (conservation of mass) of an incompressible fluid, the concept of a parachute and the sketch of a wind vane.

During the next two centuries the works of Galileo Galilei (1565–1642) [8] and Sir Isaac Newton (1642–1727) [9] resulted in a quantitative description of a basic aspect of mechanics—the motion of a mass particle. In addition to his three laws of motion, Newton formulated a statement for the resistance of a body to fluid flowing over it. Although Newton's physical concept concerning resistance was incorrect for fluids under standard pressure and temperature, his result that the resistive force is proportional in magnitude to the fluid speed squared was correct for many circumstances, particularly for bluff bodies at high Reynolds numbers which typify many wind-engineering applications. The proportionality coefficient, a quantity of great concern in wind engineering, continues to be a subject for analytical and experimental research.

The Period of 1700–1900. In the one and one-half centuries following Newton's work (1700–1850), a group of illustrious scholars developed the framework for continuum fluid mechanics which is in general use today by engineers, meteorologists and scientists. Daniel Bernoulli, d'Alembert, Euler, Navier, Cauchy, Poisson, and Stokes [10] are among the chief architects of this elegant analytical structure. However, during this same period engineers were agonizing over the inability of analysis of the day to account for the observable effects of wind and water on structures and man. This motivated serious efforts to complement analytical treatment by measurements in the laboratory and in the natural environment—a three-pronged approach which is recommended for investigation of many wind-engineering problems today. Coordinated investigations following this approach are essential for development of theory and design which will be in close harmony with physical reality.

The two-century period, 1700–1900, yielded several contributions to wind engineering which arose primarily out of the practical need to estimate wind forces on buildings and to extract energy from the wind for useful purposes. Smeaton [11] in 1759 reported on perhaps the first recorded experimental investigation of wind effects on solid objects in an artificial wind. His study of windmill-sail characteristics is significant because he recognized that "the wind itself is too uncertain to answer the purpose: we must therefore have recourse to an artificial wind." He decided to employ a rotating arm to move his model windmill through still air in a room. This method of producing relative motion between air and a solid object, used first by "Mr. Rouse, an ingenious gentleman of Harborough in Leicestershire," was employed during the ensuing 150 years to measure the resistance of solid objects moving through air.

An excellent summary of the knowledge on wind pressures related to engineering construction that existed near the beginning of the twentieth century (1895) is given by Bixby, Captain of Engineers, United States Army [12]. Results of the experimental studies reported by Duchemin [13] in 1842 had a significant impact on engineering design to minimize wind effects for many years to follow, even though much of his effort was stimulated by an interest in the exterior ballistics of projectiles.

Reynolds [14] in 1883 made basic fluid-dynamical contributions which have been of major importance in the modeling of wind effects and in describing turbulent fluid motion—the Reynolds number and the Reynolds equations of motion. In 1893 the experimental investigations of Irminger [15] to determine wind pressures on small models of buildings in a primitive wind tunnel marked the beginning of wind-effect studies in wind tunnels. This method of investigation has been used extensively ever since, and continues to grow in extent and sophistication at the present time.

The Period of 1900–1950. During the fifty-year period, 1900–

1950, investigations of wind effects were broadened in scope to include most of the areas now identified as part of wind engineering—topographic effects on wind velocity distributions and mass transport, as well as wind forces on buildings. Several fundamental developments in fluid mechanics essential for relating wind effects to atmospheric motions and to the results of laboratory investigations occurred—Prandtl [16] announced his boundary-layer concept, Taylor [17, 18] developed a statistical theory of turbulence and a theory for diffusion by continuous movements, Kármán [19] discussed the similarity of turbulent motion, and Kolmogorov [20] presented his hypotheses on the statistical characteristics of locally isotropic turbulence. Closer ties developed between fluid dynamics and meteorology through the works of Richardson [21], Bjerkness [22], Lettau [23], Brunt [24], and Prandtl [25]. A warm-cold air tunnel (16 m long, 1 m wide, 0.25 m high) was constructed at the Kaiser Wilhelm Institute for Flow Research at Göttingen by Prandtl and Reichardt [26]. This flow facility, with the lower surface cooled by tap water and the upper surface heated by steam, was the precursor of a more versatile meteorological wind tunnel to be built in the United States at a later date. In a series of papers during 1934 and 1935 on "Aerodynamics and the Civil Engineer," Pagon [27] presented a review on wind and wind effects which covers a range of topics remarkably similar in scope to that of wind engineering—aerodynamic science, stack vibrations, bridge-model tests, building-model tests, vortices and eddies, engineering meteorology, wind velocity in relation to height above ground, and design for wind.

The experiments of Stanton [28] to determine the wind-pressure distribution on structures initiated activity in industrial aerodynamics at the National Physical Laboratory (Great Britian) which has continued to this day. In 1933 Bailey [29] measured wind pressures on a railway-car shed and compared his results with measurements on a small-scale model placed in a uniform-flow wind tunnel. The agreement was poor. Later Bailey and Vincent [30] made measurements on the model shed placed in the boundary layer of a NPL wind tunnel. These pressures were found to be in better agreement with the full-scale values than were the pressures obtained in a uniform flow. Scruton [31] in 1948 commenced a series of experimental investigations in the same laboratory on the aerodynamics of suspension bridges.

Physical modeling of air flow over topographical features was initiated during this period. Pioneering experimental studies of air flow over a small-scale model of Mt. Fuji, by Abe [32], and over the Rock of Gibraltar, by Field and Warden [33], introduced the modeling of flow over complex topography which has been utilized for a variety of wind-engineering applications.

The period of 1900–1950 also brought efforts to obtain quantitative data on mass transport by wind. The work of Sherlock and Stalker [34] on dispersion of gases emitted from smokestacks introduced the use of wind tunnels for air-pollution-control investigations. In 1948, Albertson [35], motivated by the desire to promote water conservation through reduction of evaporation, applied boundary-layer concepts to an experimental study of evaporation from plane saturated surfaces which formed part of a wind-tunnel floor.

By 1950 the foundations for development of wind engineering were fairly well established and a challenge for future work was presented by Kármán [36] in a paper entitled "Aerodynamics and the Art of the Engineer."

The Period of 1950–1974. Within the last quarter century, 1950–1974, wind engineering has developed in substance and application with explosive intensity. Much of this development has taken place through application of fluid mechanics to describe wind characteristics, laboratory simulation of atmospheric motion, quantitative evaluation of wind effects such as mass transport, and wind forces on solid objects. An attempt is made in this review to identify the most fundamental applications in each of these areas.

The close relationship between fluid motion in boundary layers and atmospheric motion up to a few hundred meters above Earth's surface was clearly established by the work of O. G. Sutton [37]. In 1953 Monin and Obukhov [38] presented a first-order approximation of scaling parameters for the thermally stratified atmospheric surface layer—the lowest 30–100 m (98–328 ft)—from which the commonly used log-linear distribution for mean temperature and wind speed are derived. Panofsky [39], utilizing data obtained from a variety of field measurements, related the forms obtained by dimensional reasoning to real atmospheric behavior by specification of numerical values for the various coefficients. Examination of the power spectrum for horizontal winds at 100 m (328 ft) by Van der Hoven [40] in 1957 revealed an "energy gap" centered on a frequency of approximately 5 × 10^{-4}Hz. In 1961 Davenport [41] developed a formulation for the energy spectrum of horizontal turbulence near the ground which has been found to be in good agreement with measurements made under strong wind conditions. Many efforts have been made to describe the entire planetary boundary layer, as revealed by the review of Hanna [42]. The simplest analysis of the basic equations of motion was presented by Lettau [43] and yielded wind spirals in fair agreement with wind observations.

Concentrations of vertical vorticity in the form of hurricanes and tornadoes were studied intensively. Efforts to develop quantitative descriptions of these atmospheric singularities were highlighted by the hurricane model hypothesized by Carrier, Hammond and George [44], and the analysis of tornado-like atmospheric vortices by Kuo [45, 46].

Requirements for simulation of atmospheric motions and the development of laboratory facilities for this purpose were subjects of intense study during the period 1950–1974. Fultz [47, 48] reviewed experimental analogies to atmospheric motions and examined non-dimensional forms of the equations of motion in an effort to establish modeling criteria. The work of Fultz focused primarily on modeling of large-scale (global-scale) atmospheric motions which are of secondary importance to wind engineering; however, the methods used served as guidance for investigation of similarity requirements within the atmospheric boundary layer. Rouse [49] suggested that the conventional aeronautical wind tunnel might serve as the starting point for design of a laboratory facility to simulate the atmospheric boundary layer. Cermak, Sandborn, Plate, Binder, Chuang, Meroney and Ito [50] and Cermak and Arya [51] developed similarity criteria for simulation of the atmospheric boundary layer based on the development of thick thermally-stratified turbulent boundary layers—1 m (3.3 ft)—over the floor of a long wind-tunnel test section—30 m (98 ft). In 1966 a colloquium organized by Hidy [52] reviewed and recorded the current state of knowledge on atmospheric simulation.

Modification of the conventional aeronautical wind tunnel to enable simulation of thermally stratified boundary layers took place in 1952 with the work of Strom [53]. Stratification was achieved by inserting a vertical array of horizontal heating wires at the test-section entrance. Cermak [54] reported on initial development of a unique meteorological wind tunnel which was completed in 1963. Characteristic features of this long-test-section facility—30 m (98 ft)—with heating and cooling capabilities in both the test-section floor and in the return-flow section are described by Plate and Cermak [55]. In 1969 Clark [56] reported use of a water channel to investigate stability of stratified shear flows. Stratification was achieved by introducing water at different temperatures through horizontal rows of jets arranged in a vertical array to fill the entire channel entrance.

Many wind-water channels were constructed to investigate air-sea interactions. The facility designed by Plate [57] was novel in that the entire channel could be tilted about a horizontal hinge to produce water flow in a direction either the same or opposite to the direction of air flow. A 40 m (131 ft) long by 3.2 m (10 ft) wide wind-water channel constructed at Marseille was described by Coantic, Bonmarin, Pouchain and Favre [58] in 1969. This facility provided for boundary-layer removal from walls of the air passage, temperature control of the air and water, relative humidity control of the air, and mechanical generation of waves.

Numerous efforts were made to simulate atmospheric boundary layers in short-test-section wind tunnels by modifying flow at the test-section entrance with jets, vortex generators, grids, fences, spires, roughness plates, screen, etc.—Teunissen [59]. The system of vortex generators with a barrier developed by Counihan [60] was a noteworthy contribution to the problem of utilizing many existing aeronautical-type wind tunnels for wind-engineering purposes.

Contributions during the last 25 years to knowledge on wind effects have resulted from analysis, laboratory investigations and full-scale or field measurements, with the most notable advances resulting when all three approaches were used in combination. Efforts which significantly stimulated the use of simulated atmospheric boundary layers for investigations of mass transfer by the atmosphere and wind pressures on buildings were reported by Cermak and Koloseus [61] and by Jensen [62], respectively. The former research was on evaporation rates from a 1:2000 scale model of Lake Hefner (near Oklahoma City) placed in a wind tunnel which provided a well-developed turbulent boundary layer, and from the actual lake. This investigation revealed that evaporation rates for both the laboratory and prototype flow are related to surface shear stress by the same relationship. In the latter study, wind pressures were measured on a small building in the atmosphere and on a 1:20 scale model placed in a wind tunnel. Mean-pressure distributions for the two scales of motion were found to be the same provided that the ratio of building height to the upwind aerodynamic roughness length was the same and that the turbulent boundary-layer thickness in the wind tunnel was several times greater than the building height. These two investigations, in which laboratory data were confirmed by full-scale measurements, revealed that proper simulation of the atmospheric boundary layer is essential for reliable determination of wind effects by measurements on small-scale models.

By 1960 many of the theoretical aspects of turbulent diffusion had been applied to diffusion in the atmospheric boundary layer. Stimulated by the growing concern about air pollution, health hazards from radioactive products of nuclear processes, and the possibilities for augmenting rainfall by cloud seeding, Pasquill [63] presented an organized treatment of atmospheric diffusion. Statistical theory was applied to the description of turbulence and turbulent diffusion well before 1950; however, Davenport [64] first applied statistical concepts to the description of wind loading of structures in 1961. A subsequent paper by Davenport [65] presented statistical methods which enable specific wind effects on structures to be predicted from the combined use of climatological data and data obtained from measurements on a small-scale wind-tunnel model.

Requirements for dynamic similarity of a model structure were given by Whitbread [66]. Wind-excited oscillations of stacks, towers and masts were discussed by Scruton [67], with emphasis on aerodynamic characteristics and geometrical features for the reduction of oscillation amplitudes. Farquharson [68]; Scruton [69]; Hirai, Okauchi and Miyata [70]; Scanlan [71] and Tanaka and Davenport [72] provided a series of definitive papers on aerodynamic stability and wind-induced motions of suspension bridges. Pioneering aerodynamic investigations of a fundamental nature on oscillations induced by galloping and vortex shedding were made by Roshko [73], Den Hartog [74], Parkinson [75], Novak [76], and Novak and Tanaka [77]. They have added much to the understanding of wind-induced oscillations. An excellent review of the action of wind on suspension bridges was given by Davenport [78] in a lecture at the International Symposium on Suspension Bridges held in Lisbon, Portugal in 1966.

Out of the extensive use of lightweight cladding and large glass windows on the exterior surface of buildings came a need to investigate the fluctuation statistics of local wind pressures. Cermak [79], Sadeh and Cermak [80], and Peterka and Cermak [81] identified the causes for large fluctuations and established characteristic features of their probability distributions. Sadeh, Sutera, and Maeder [82] and Hunt [83] made significant advances in relating turbulence properties of the approaching wind to pressure characteristics on the upwind face of a solid surface. Measurements on full-scale structures yielded not only direct information on wind effects but also provided a data base which may be used to determine how well data obtained from small-scale models predict full-scale behavior. The first measurements used for this dual function were those from a study of mean pressures on a low-rise building with a flat roof near Brussels by Colin and D'Have [84]. Full-scale studies of special note in which pressure fluctuations were measured were those of Newberry, Eaton and Mayne [85] on a circular building, and Dalgleish [86] and Miyoshi, Ida, and Miura [87] on rectangular buildings. Measurements of dynamic response resulting from wind action on full-scale towers were compared with analytical predictions resulting from a simulated wind by Chiu and Taoka [88] and Schueller and Wittman [89].

Wind engineering was identified as a distinct discipline in the United States only near the close of the last quarter century. The event which marked this recognition was a Conference on Wind Loads on Structures [90], which was redesignated as the First U.S. National Conference on Wind Engineering Research. At this Conference a Wind Engineering Research Council was organized to provide a mechanism for the free exchange of information on research plans, priorities, and programs.

The European counterpart of wind engineering was identified as industrial aerodynamics. This discipline, which includes internal flow of gases as well as external flow associated with atmospheric motion, grew primarily from research at the National Physical Laboratory (Great Britain) and was identified as such by Scruton [91] and Rogers and Whitbread [92]. An outcome of these efforts was initiation of a series of International Conferences on Wind Effects on Buildings and Structures. The First Conference (1963) was in Teddington, England; the Second (1967) was in Ottawa, Canada; the the Third (1971) took place in Tokyo, Japan.

3 Wind Characteristics

Efforts to develop designs and plans which account for wind effects in a rational manner have always been frustrated to some degree by the uncertain variability of wind. Pressure differences arising from unequal heating of Earth's surface by solar radiation provide the basic driving forces which produce wind. The resulting systems of atmospheric motion vary in size from global diameter to a few meters, as other forces are brought into action by the rotation of Earth, cloud cover, precipitation, nonuniform surface temperature and roughness, and topographic relief. Nonlinear interactions between the fluid systems of different scales and with forces resulting from the variety of causes that have been indicated produce winds with characteristics which vary in an almost random manner. Accordingly, statistical parameters formulated for the statistical description of turbulence provide a useful description of the wind [14, 93].

Most of the wind data recorded over significant time periods has been obtained from measurements at several elevations on towers at widely spaced locations. Parameters most commonly of concern are the temporal averages of wind speed and temperature, variances of velocity components, recurrence periods for maximum wind speeds, probability that wind from a given direction will have a specified speed, energy spectra for the velocity fluctuations, and cross-correlation of vertical and longitudinal velocity components. Elaborate numerical models constructed from the fundamental equations of fluid mechanics are being developed and tested in an effort to predict future states of the atmosphere when an initial state is known [94]. However, this effort, even if successful, will not be of substantial use to the wind engineer who is concerned about wind behavior at a given location for 50 to 100 years in the future. His decisions must be based upon use of recorded data and statistical methods to determine the mean recurrence interval for certain meteorological events, e.g., the mean annual extreme-mile (fastest-mile) wind speed at 9 m (30 ft) above the ground surface [95]. Kessler [96] surveyed available wind data within the boundary layer and has presented typical probabilities for extreme values of wind speed which can be used to estimate variances from the mean data.

Statistical information describing wind characteristics at a point in space must be extended locally by consideration of fluid-mechanical restraints placed upon the flow. Fortunately, local organization of flow structure which approximates the form of a classical turbulent boundary layer exists most of the time. Storms with strong vertical components of vorticity, such as hurricanes and tornadoes, modify or destroy the boundary-layer structure and develop an organized structure in the horizontal plane. Winds with poorly defined spatial structure are found to be associated with low-level jets, down-slope winds, thunderstorms, and local topographic effects. Description of these many types of winds for wind-engineering purposes requires extensive applications of fluid mechanics—applications as essential as for the description of wind effects themselves.

Boundary-Layer Winds. Most of the time, atmospheric motion up to about 1,000 m (3,300 ft) above the surface is of the boundary-layer type and is usually designated as the planetary boundary layer. Separation in the lee of hills or mountains, severe thunderstorms, and tornadoes are responsible for the greatest deviations from boundary-layer structure. A detailed description of flow characteristics in the planetary boundary layers which can account for all the perturbing effects of nonuniform and unsteady surface-flow conditions, topography and thermal stratification has not been possible. However, descriptions for idealized conditions have been formulated and serve as frames of reference. Hanna [97] reviewed fourteen different analytical and numerical models and concluded that the models developed by Lettau [43] and Blackadar [98] represent wind observations fairly well. A typical distribution of mean wind speed with height for a rough surface, as determined from the model of Lettau [43], is shown in Fig. 1. For this model the atmosphere is taken to be steady, horizontally homogeneous, dry, and adiabatic, with no vertical motion, invariant variances of velocity fluctuations, and a negligible effect of the turbulent energy dissipation rate on temperature. The equations of motion for this case are simply

$$f(V - V_g) - \frac{\partial}{\partial z} <u'w'> = 0 \tag{1}$$

and

$$f(U_g - U) - \frac{\partial}{\partial z} <v'w'> = 0. \tag{2}$$

Reynolds stresses were related to the mean velocities by an eddy viscosity K_M as follows:

$$<u'w'> = -K_M \frac{\partial U}{\partial z} \tag{3}$$

and

$$<v'w'> = -K_M \frac{\partial V}{\partial z} \tag{4}$$

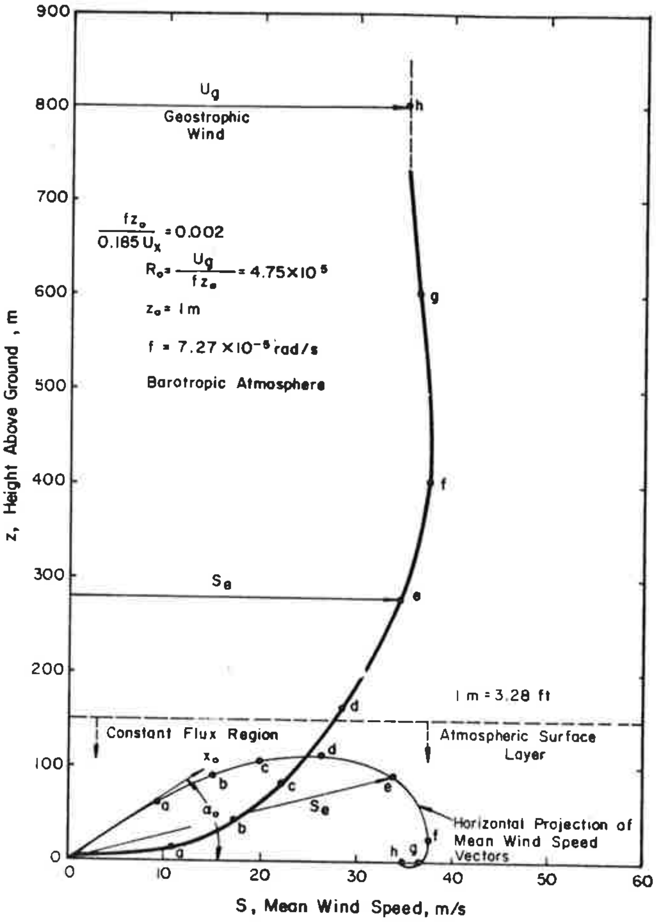

Fig. 1 Planetary boundary layer according to model of Lettau [43]

To complete the system, Lettau selected a form for K_M in terms of a mixing length $l(z)$ as follows:

$$K_M = l^2(z) \left[\left(\frac{\partial U}{\partial z} \right)^2 + \left(\frac{\partial V}{\partial z} \right)^2 \right]^{1/2} \tag{5}$$

$$\frac{l(z)}{L_M} = \frac{0.4z/L_M}{1 + 4(z/L_M)^{5/4}} \tag{6}$$

where L_M is a scale height chosen to be

$$L_M = 0.0736\, u_*/f. \tag{7}$$

Although the foregoing formulation contains gross approximations and physical compromises, it does specify the nondimensional functional forms

$$\frac{U}{u_*} = F_1 \left(\frac{fz}{u_*}, \frac{U_g}{fz_0} \right) \text{ and} \tag{8}$$

$$\frac{V}{u_*} = F_2 \left(\frac{fz}{u_*}, \frac{U_g}{fz_0} \right), \tag{9}$$

when a numerical integration is performed subject to the appropriate boundary conditions. Thus, specification of the surface Rossby number—Ro = $U_g/(fz_0)$—defines a "universal" vertical distribution of nondimensional mean velocity components in terms of the nondimensional height fz/u_*. This in turn determines the angle α_0 which the surface shear stress τ_0 makes with the isobars, as shown in Fig. 1. Both the surface shear stress and the surface drag coefficient u_*/U_g determined from the Lettau model are shown with data from field measurements in Fig. 2 as a function of Ro. These data for a barotropic (air density a function of only pressure) atmosphere are in fair agreement

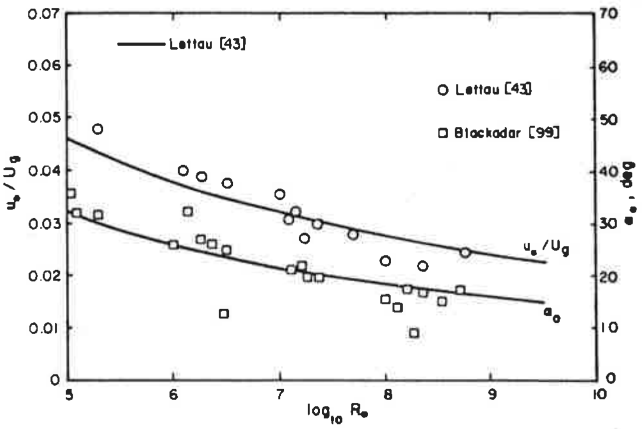

Fig. 2 The surface drag coefficient u_*/U_g and surface cross-isobar angle α_0 as functions of surface Rossby number R_0 [97]

with predictions of the model; however, data for baroclinic (air density not a function of only pressure) atmospheres show much more scatter [99]. Analysis of low-level radiosonde and rawindsonde data for areas of the eastern United States by Hoxit [100] reveal that the balance of pressure gradient, Coriolis, and frictional forces assumed in the foregoing model exists only during afternoon hours. Panofsky [39] reports that further study of the planetary boundary layer since 1970 indicates that in addition to Earth's rotation, surface roughness and stability within the layer, the surface drag coefficient may depend also upon stratification and vertical motion in the atmosphere above the planetary boundary layer.

Thus, it is evident that fluid mechanics of the planetary boundary layer is not completely understood and that the model described serves to define only a small class of possible mean states—no description of turbulence statistics is provided. More realistic mathematical models have been formulated by Deardorff [101], Donaldson [102] and Lumley and Khajeh-Nouri [103] which attempt to take into account turbulence transport mechanisms. These complex models may, through fundamental scientific research, increase our understanding of atmospheric boundary layers but do not appear to provide an immediate tool for the practice of wind engineering.

Wind-engineering applications may be placed in two broad categories with respect to the thermal stratification and region of the boundary layer which significantly influence the wind effect of interest. Consideration of wind forces on buildings and structures requires information on boundary layers during strong winds. Thermal stratification is usually destroyed by intense mixing for strong-wind conditions; therefore, boundary layers with no thermal stratification (adiabatic lapse rate) are appropriate for most wind-force studies. When the structures are tall and extend over most of the planetary-boundary-layer depth, wind forces are affected by the entire boundary layer. Invesitgations of local air-pollution problems and mass transport in urban areas, on the other hand, require information on weak-wind boundary layers. Under this condition, thermal stratification over the lower region of the planetary boundary layer (the atmospheric surface layer as indicated in Fig. 1) strongly affects the turbulent mixing and must be accounted for. Both of these categories of atmospheric motion are special cases of the general flow discussed previously and are described more readily.

Vertical profiles of mean wind speed for strong-wind boundary layers are approximated by taking the wind speed to be proportional to the height raised to some power—a "power-law" variation. The simple expression which is used extensively has the form

$$\frac{U}{U_g} = \left(\frac{z}{z_g}\right)^{1/n} \qquad (10)$$

where the value of n depends upon the surface roughness and must be related to the aerodynamic roughness length z_0 by fitting to observed data. The power-law profile appears to have been suggested first in 1885 by Archibald [104] when attempting to correlate wind speeds recorded by pairs of anemometers hung from kites. This form was probably inspired by the fact, known at that time, that for laminar flow in a circular tube flow speed increases as the one-half power of distance away from the wall. In fact, as Earth's surface roughness nears 10 m (33 ft) the value of n approaches a value of 2. For such cases the eddy viscosity becomes fairly constant throughout the boundary layer to produce a momentum-transfer-rate distribution similar to that produced by constant molecular viscosity in laminar flow.

Further support for the power-law formulation comes from the approximate equality of n for the neutral atmospheric boundary layer over flat, open grassland—z_0 approximately equal to 0.02 m (0.066 ft)—and for the flat-plate, zero-pressure-gradient, aerodynamic boundary layer developed in wind tunnels, i.e., $n = 7$ [105]. By analysis of published wind data for 19 different sites, Davenport [106, 107] was able to establish how n and the geostropic wind height z_g varies with z_0 in strong winds. These relationships are shown in Fig. 3. Development of analytical relationships between these variables from basic physical principles continues to be a challenge for the fluid dynamicist.

A description of turbulence throughout the entire planetary boundary layer, even for only strong winds, has not been formulated. This is due partly to a lack of adequate data up to 500 m (1,600 ft) above the surface; however, data are becoming available from several tall towers which have been instrumented during the past few years. Also, complex interactions of the outer part of the boundary layer with upper air motions make organization of the data difficult (but provide a fertile area for research).

In a review of turbulence in the atmospheric boundary layer, Monin [108] presented a set of energy spectra for vertical turbulence at heights up to 2,000 m (6,600 ft). These data are shown in Fig. 4 and reveal that, as the height is increased from the surface to the upper edge of the surface layer, turbulent energy content increases and then decreases as the elevation continues to increase. Furthermore, the wave number for peak energy content decreases as the elevation increases. These results show what is thought to be a typical distribution of turbulence. Aside from effects on propagation of electromagnetic radiation, details of turbulence in the outer reaches of the boundary layer have application in the determination of wind forces on very tall buildings and towers. For the latter purpose, simulated atmospheric boundary layers are relied upon to generate the proper

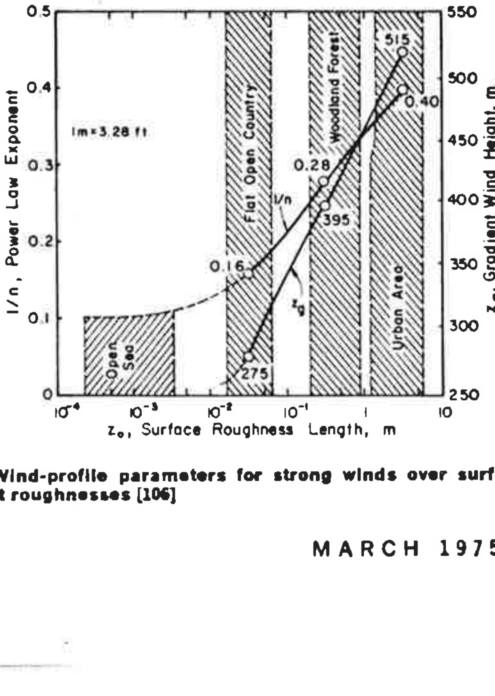

Fig. 3 Wind-profile parameters for strong winds over surfaces of different roughnesses [106]

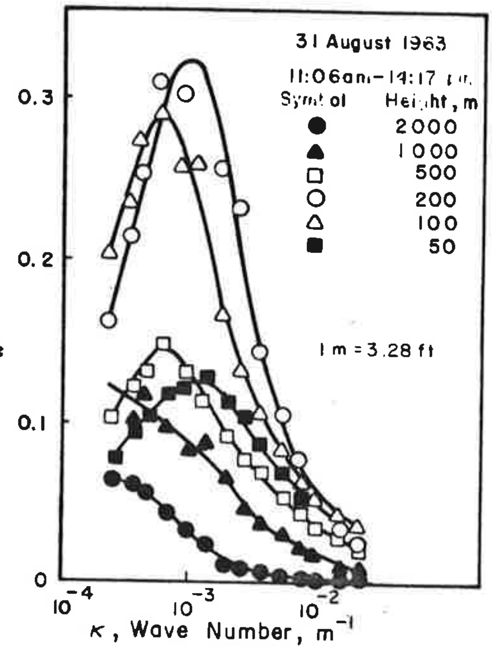

Fig. 4 Spectra of vertical velocity in the planetary boundary layer [108]

turbulence structure and wind effects on small-scale models, as described by Cermak [109].

Most of the wind-engineering applications occur in the lowest 100–150 m (325–500 ft). Flow in this layer is much easier to relate to local surface parameters; therefore, with the abundant micrometeorological data available from many towers, construction of a coherent description of the atmospheric surface layer has been possible.

Winds in the atmospheric surface layer are of concern primarily because of their effects on both local diffusion and transport of air pollutants, and their development of wind forces on buildings and structures. Therefore, both the characteristics of weak winds and strong winds must be considered. For extensive plane surfaces with uniform roughness (elements small compared to thickness of surface layer) and uniform surface heat flux and surface temperature, Monin and Obukhov [38] considered the flow statistics to have planar-homogeneity in planes parallel to the surface. They assumed that variables affecting the flow structure are: height above the boundary z, fluid density ρ, surface shear stress τ_0, surface heat flux H_0, 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:

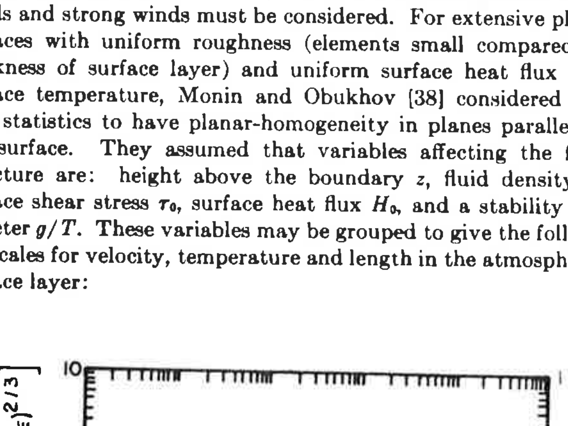

Fig. 5 Spectra of vertical velocity in the atmospheric surface layer, after Kaimal et al., [113], as presented by Panofsky [39]

shear velocity $u_* = (\tau_0/\rho)^{1/2}$ (11)

friction temperature $T_* = -H_0/(\rho C_p k' u_*)$ (12)

Monin-Obukhov length $L = -u_*^3/[(k'g/T)H_0/\rho C_p]$ (13)

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 the mesoscale disturbances passing though the flow, as may happen for very stable flows.

When the thermal stability does not depart strongly from neutral stability ($L \to \infty$), the dimensionless wind shear $(k'z/u_*)(\partial U/\partial z)$ and temperature gradient $(z/T_*)(\partial T/\partial z)$ may be approximated by linear functions of z/L [38]. 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:

$$U(z) - U(z_{\text{ref}}) = (u_*/k')[\ln (z/z_{\text{ref}}) + B_U(z - z_{\text{ref}})/L] \tag{14}$$

and

$$T(z) - T(z_{\text{ref}}) = T_*[\ln (z/z_{\text{ref}}) + B_T(z - z_{\text{ref}})/L]. \tag{15}$$

These distributions reduce to the well-known logarithmic profiles for neutral stability ($L \to \infty$) when z_{ref} is set equal to z_0.

On the basis of Monin-Obukhov similarity, turbulence statistics in the surface layer can be scaled by the scaling factors expressed by equations (11)–(13). In particular, the standard deviation of vertical-velocity fluctuations may be expressed in the form

$$\langle w'^2 \rangle^{1/2}/u_* = \phi_1(z/L). \tag{16}$$

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 [39], Lumley and Panofsky [93], Businger [110], and Kaimal [111].

Turbulence spectra in the surface layer have been correlated through use of Monin-Obukhov scaling [39, 112] and Kolmogorov scaling has been used to compare atmospheric spectra with spectra in simulated boundary layers [4]. Spectra of vertical-velocity fluctuations are ordered by Monin-Obukhov scaling better than are the lateral and longitudinal components. Data obtained in the Kansas field experiment follow a systematic variation with the parameters z/L and $\omega z/U$ as given by Kaimal, Wyngaard, Izumi, and Coté [113], and are shown in Fig. 5 as presented by Panofsky [39]. When the flow is neutral they propose the following form for the normalized spectra:

$$k_1 E_w(k_1)/u_*^2 = 2k_1 z/[1 + 5.3(k_1 z)^{5/3}] \tag{17}$$

where $k_1 = 1/(2z)$ is the wave number for maximum energy, i.e., the vertical gusts of greatest energy at a particular height have a size about twice the height. The spectra for horizontal fluctuations have not been found to scale directly with height for a wide range of thermal stratification [39]. However, a useful form for the longitudinal-velocity spectra in strong winds (essentially neutral) has been given by Davenport [107]. This form, developed through a study of spectra for strong winds, is given by

$$\omega E_u(\omega)/u_*^2 = 4 \frac{x^2}{(1 + x^2)^{4/3}} \tag{18}$$

where $x = 4{,}000\ \omega/U_{10}$; ($U_{10}$ is mean wind speed at 10 m). Equation (18) gives spectra which are independent of height, and do not reflect the height dependency expected to follow from the vertical-velocity spectra shown in Fig. 4.

At high Reynolds numbers, Kolomogorov [20] makes the hypothesis that a high-wave-number range exists in the turbulence spectrum which is governed by the kinematic visocisty ν and the energy dissipation ϵ. The corresponding length and velocity scales are $(\nu^3/\epsilon)^{1/4}$ and $(\nu\epsilon)^{1/4}$, respectively. These scaling factors provide a basis for comparing turbulence spectra for similarity. For example, one-dimensional longitudinal-turbulence spectra can be related as follows:

$$[(u'^2)E_u(\kappa)]/(\epsilon\nu^5)^{1/4} = \phi_2[\kappa(\nu^3/\epsilon)^{1/4}] \tag{19}$$

where κ is the wave number.

The foregoing spectra represent the microscale' fluctuations developed primarily by mechanical and thermal action. Van der Hoven [40] examined the spectrum of longitudinal fluctuation at 100 m (330 ft) on the Brookhaven tower for frequencies down to 2×10^{-7} Hz and reported the significant results shown in Fig. 6. The spectra of equations (17) and (18) are at frequencies greater than values within the "spectral gap." Fluctuations at frequencies smaller than the spectral-gap frequencies define the climatological characteristics of a site and are affected by geographical latitude, topography and location relative to large bodies of water.

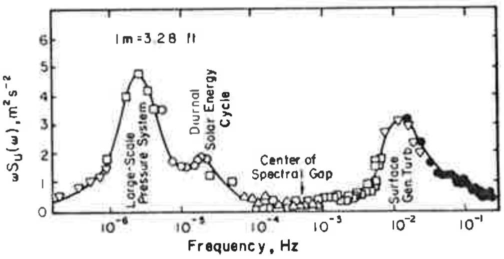

Fig. 6 Spectra of longitudinal velocity at 100 m (330 ft), from Van der Hoven [40]

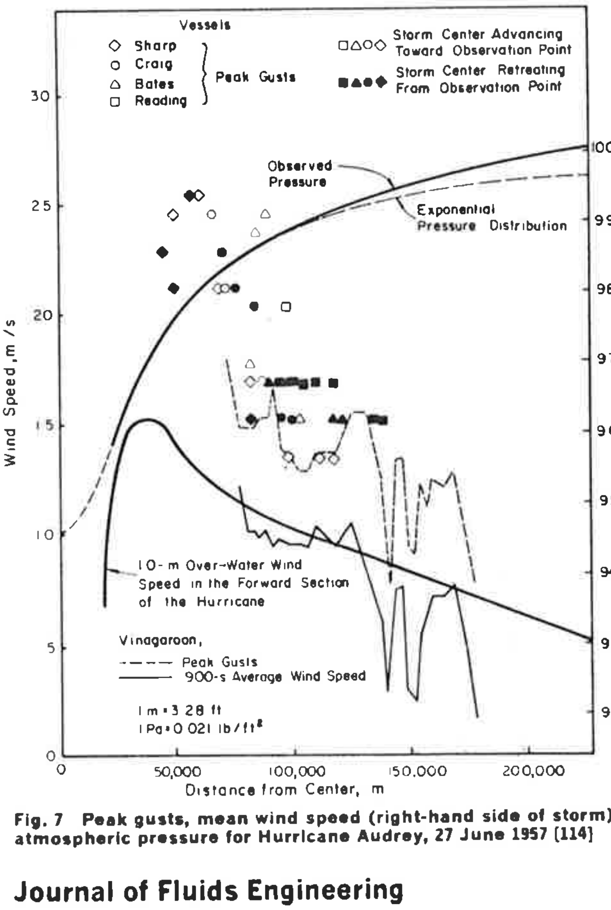

Fig. 7 Peak gusts, mean wind speed (right-hand side of storm) and atmospheric pressure for Hurricane Audrey, 27 June 1957 [114]

The mean-velocity and turbulence characteristics described have been for sites where the surrounding surface is flat and uniform for distances sufficiently large to attain a fully-developed boundary layer over the site. However, the usual surface conditions near an urban site are nonuniform and may be complicated by high roughness elements and topographic features. When these complications occur the foregoing information may serve only as a reference, and simulation of the wind field by physical modeling of a specific site becomes necessary for definition of both the wind field and the wind effects of interest.

Hurricane Winds. Hurricanes and typhoons originate over large warm bodies of water and derive energy from latent heat released by condensing water vapor. The general motion is organized in a swirling pattern with strong vertical vorticity distributed over an area up to several hundred miles in radius which, in the northern hemisphere, rotates counterclockwise when viewed from above. This entire flow pattern, in turn, translates with speeds in the 2 – 9 m/s (7 – 28 ft/s) range.

Wind and pressure data for Hurricane Audrey, processed by Graham and Hudson [114], are shown in Fig. 7. In the core area, out to about 32 km (23 mi) from the center, motion is comparable to a solid body rotation ($V_\theta r^{-1}$ = Constant) and the air is very warm. The typical, almost cloudless, appearance of a hurricane core is illustrated by Fig. 8. For distances beyond the core Elsberry, Pearson and Corgnati [115] take the circumferential velocity at the top of the boundary layer as $V_\theta r^{1/2}$ = constant.

The most fundamental fluid-dynamical model of a hurricane that has been developed in the one by Carrier, Hammond, and George [44]. Fig. 9 shows the radial distribution of motions which illustrates the circulation pattern hypothesized by these investigators. The model predicts the distribution of mean quantities, but no progress has been made in predicting the

Fig. 8 Hurricane Betsy photographed from Gemini 5 at 18 km (11 mi) elevation on 3 September 1965 (Photograph by U. S. Air Force Air Weather Service made available by the National Hurricane Research Laboratory).

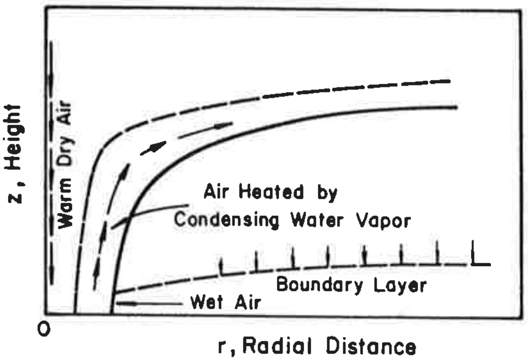

Fig. 9 Radial circulation in a hurricane [44, 114]

Fig. 10 Tornado of 5 June 1966 at Enid, Oklahoma (Photograph by Leo Ainsworth provided by National Severe Storms Laboratory, Norman, Okla.)

magnitude of gusts, which become very large near the outer region of the core as shown in Fig. 7.

Flow characteristics in the boundary-layer region outside the core are described satisfactorily by the formulations given previously. As the storm moves from sea to land the wind intensity begins to decay, but decreases only by about 30–40 percent in the first 100 miles of travel over land.

Tornadoes. The most intense, but least defined, winds result from highly concentrated vertical vorticity. These atmospheric singularities are known, in order of decreasing intensity, as tornadoes, waterspouts and dust devils—maximum wind speeds are in the ranges of 40–150 m/s (130–490 ft/s), 20–80 m/s (65–260 ft/s) and 10 m/s (33 ft/s), respectively [116]. Whereas the hurricane may have a diameter of about 1,000 km (620 mi), the diameter ranges for tornadoes, waterspouts and dust devils are 100–3,000 m (300–10,000 ft), 10–100 m (30–300 ft) and 10 m (33 ft), respectively. Instructive presentations on waterspouts by Golden [116], on tornadoes and hurricanes by Penner [117], and on geophysical vortices in general by Morton [118] should be consulted for a description of many details of these phenomena.

The tornado (at Enid, Oklahoma on 5 June 1966) shown in Fig. 10 illustrates typical physical characteristics of a tornado and helps to appreciate why so little data on these phenomena are available. Photographic data sufficient to determine the wind field have been obtained by Hoecker [119], but for only one tornado—the Dallas tornado of 2 April 1958. At an elevation of 300 m (1,000 ft) the inner core had a radius of about 67 m (220 ft) and the overall radius was 414 m (1,360 ft). The Rankine combined vortex with a core of solid body rotation—out to 67 m (220 ft)—and a speed variation of Vr = constant beyond the radius for maximum speed was found to be a good model at this elevation. At 45 m (150 ft) elevation the core was about 50 m (170 ft) in radius. Beyond the 45 m (150 ft) radius the tangential speed decreased from the maximum of 74 m/s (241 ft/s) more rapidly than for the classical vortex—as V = constant $r^{-1.6}$ initially. Isotachs for tangential and vertical wind speeds near the surface are shown in Figs. 11 and 12.

A first-order approximation of the radial equation of motion results in the cyclostrophic wind equation

$$\frac{\partial P}{\partial r} = \rho \frac{V^2}{r} \tag{20}$$

which may be used to estimate pressure in the tornado core from the deduced tangential speed distribution. Using this method Hoecker [120] estimated the pressure at ground level to be 6,200 *Pa* (130 lb/ft²) below the ambient pressure at r = 457 m (1,500 ft).

Tornadoes form in many sizes and with a wide range of maximum wind speeds; therefore, the Dallas tornado data can serve best as a check on tornado models, rather than for design purposes. Fujita [121] has proposed a classification scale for tornadoes after study of the available data for many tornadoes. The F-scale classification is continuously being upgraded and evaluated as more data become available [122]. Estimations of the maximum wind speeds to be found in tornadoes have ranged from near sonic speed to the more acceptable values (based on accumulating evidence) of 44–88 m/s (144–288 ft/s) suggested by Dergarabedian and Fendell [123].

Nuclear facilities must be designed to be able to interact directly with a tornado without compromising safety of the public. Potential damage due to external wind loading, pressure differences between the inside and outside of buildings resulting from rapid passage of the low-pressure core over a building, and impact from wind-driven missiles all require an estimate of the

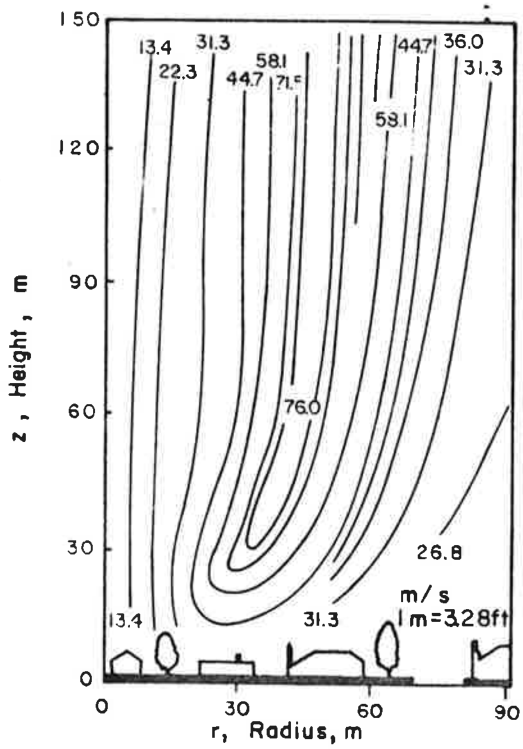

Fig. 11 Isotachs for tangential wind speeds in Dallas tornado of 2 April 1957, derived from motion pictures of debris [119]

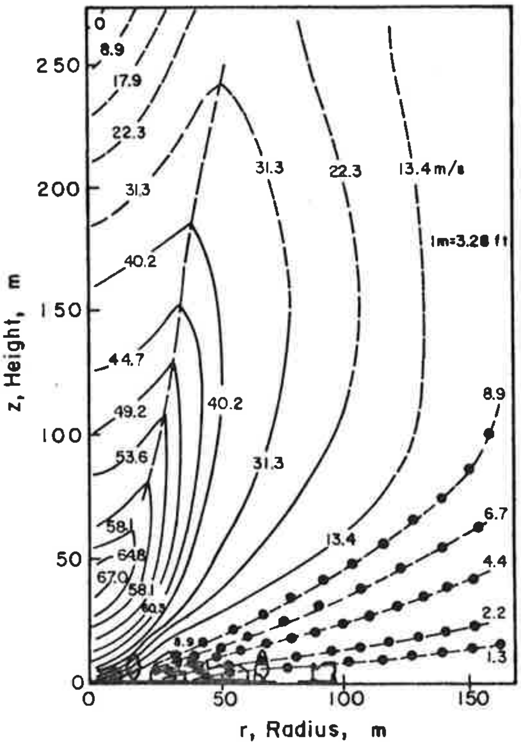

Fig. 12 Isotachs for vertical (upward) wind speed in Dallas tornado of 2 April 1957, derived from motion pictures of debris [119]

tornado wind field. After a study of tornado statistics throughout the United States the U.S. Atomic Energy Commission [124] issued a set of tornado properties for tentative use until modifications can be made on the basis of new data. For the continental United States east of the Rocky Mountains, a maximum wind speed of 161 m/s (528 ft/s) (130 m/s rotational speed plus 30 m/s translation speed) and a pressure drop of 20,680 Pa (432 lb/ft^2) at a rate of 13,800 Pa/s (288 lb/ft^2-s) were proposed. Lower values are suggested for all other regions.

Two recent analytical efforts to describe tornado winds have been made by Kuo [125] and Nicholson and Johnson [126]. In the former work the flow is described by a boundary-layer-type flow near the surface which is matched with a similarity solution for the outer (upper) motion. In the latter investigation, the Rankine combined-vortex model is modified by considering the effects of frictional forces due to lateral and vertical wind shear. Turbulence properties are not considered.

Other Wind Types. Strong winds not of the classical boundary-layer type or vortex type (hurricanes, tornadoes, waterspouts, etc.) occur and can have important effects on buildings and structures. Low-level jets, for which maximum wind speeds up to 30 m/s (98 ft/s) may occur at low elevations of about 750 m (2,460 ft), occur frequently in the Great Plains of the United States [127]. This type of flow behaves somewhat like the classical wall jet; however, insufficient data are available to specify an exponent for a power-law approximation to the "boundary-layer" flow between the surface and the wind-speed maximum.

Strong downslope winds (foehn, bora, cold-air foehn) are local in nature and are characterized by strong mean speeds and exceptionally strong gusts [128]. At an elevation of 11 m (36 ft), the one-half hourly mean wind speed attains values of 27 m/s (88 ft/s) and the gusts exceed 45 m/s (148 ft/s). The detailed structure of these flows and the mechanism which drives them have not been established.

Winds in strong thunderstorms are known to produce extensive damage. Unfortunately, these winds are so chaotic and difficult to measure that very little can be said about their properties at this time.

Summary of Research Needs. Wind characteristics in the atmospheric surface layer are well defined because of extensive measurements in the lowest 100 m (330 ft) of the atmosphere. However, extensive measurements in the outer region of the planetary boundary layer are required to obtain adequate definition for wind-engineering purposes. Measurements in strong winds to heights of at least 1000 m (3280 ft) to determine the height dependence of the turbulence energy spectrum, turbulence length scales, and turbulence space correlations for all three components of turbulence are urgently needed. Wind characteristics over city complexes are of particular concern.

Turbulence and mean-wind-speed data in the eye-wall region of hurricanes, tornadoes, down-slope winds, low-level jets, and thunder-storms are very scarce. Intensive efforts to develop remotely controlled sensing systems for flight into these transient storms, particulary the tornado, are needed to overcome this deficiency. Until this has been accomplished, post-storm inspection of damage to obtain indirect information on storm-wind characteristics should be continued and intensified.

Much of the research required to extend our knowledge of wind characteristics is the task of meteorologists and atmospheric scientists. However, participation of wind engineers to specify the type of wind data required for engineering purposes is essential.

4 Simulation of the Wind

Fluid-mechanical descriptions of wind and physical descriptions of wind effects must be available if wind engineering is to be practiced on a rational and objective basis. Both of these needs can be met, at least partially, through use of simulated winds. There are two fundamental approaches to simulation—physical modeling and numerical modeling.

Physical modeling in wind tunnels has great flexibility for simulation of planetary boundary layers subjected to realistic surface conditions [4]. Perturbed forms of the uniform-surface boundary layers described in Section 3 and local flow around obstacles can be realized for surface conditions as complex as an urban area.

Numerical modeling, on the other hand, has progressed to the stage where various formulations for the turbulent processes can be investigated to determine their ability to predict flow characteristics in the boundary layer. However, this is now feasible for only uniform surface conditions or a two-dimensional step change in surface conditions [39, 129]. Because physical modeling provides the only direct attack for investigation of local winds and wind effects under complex boundary conditions which characterize most of the wind-engineering applications, the fluid-mechanical basis for this technique will be emphasized.

Requirements for Physical Modeling of the Atmospheric Boundary Layer. The basic physical model is a boundary layer formed over the floor of a long wind-tunnel working section in which vertical temperature gradients are controlled by heating or cooling the floor and by cooling or heating the ambient air stream. The effects of radiation transfer and phase changes of water in the atmosphere are not included in the physical modeling currently being done. Accordingly, neither the simulation of local singular motions associated with thunderstorms and tornadoes nor wash-out and rainout of pollutants by precipitation are achieved. The development of elevated inversions in the boundary layer, either by ground radiation or by subsidence of the upper atmosphere, is of extreme importance. These must be included in the model as an upwind boundary condition since the local physical processes for their development are not usually present in the model.

The general requirements for geometric, dynamic and thermic similarity can be obtained directly by inspectional analysis—a method described by Ruark [130] to supplement dimensional analysis. Appropriate equations expressing the fundamental concepts of mass, momentum and energy conservation for motion of the atmosphere may be scaled to yield the following forms [4]:

$$\frac{\partial \rho^*}{\partial t^*} + \frac{\partial(\rho^* u_i^*)}{\partial x_i^*} = 0, \tag{21}$$

$$\frac{\partial U_i^*}{\partial t^*} + U_j^* \frac{\partial U_i^*}{\partial x_j^*} + \left[\frac{L_0\Omega_0}{U_0}\right] 2\epsilon_{ijk}\Omega_j^* U_k^* = -\frac{\partial P^*}{\partial x_i^*} - \left[\frac{\Delta T_0}{T_0}\,\frac{L_0 g_0}{U_0^2}\right]\Delta T^* g^* \delta_{i3} + \left[\frac{\nu_0}{U_0 L_0}\right]\frac{\partial^2 U_i^*}{\partial x_k^* \partial x_k^*} + \frac{\partial < -u_i' u_j' >^*}{\partial x_j^*}, \tag{22}$$

and

$$\frac{\partial T^*}{\partial t^*} + U_i^* \frac{\partial T^*}{\partial x_i^*} = \left[\frac{k_0}{\rho_0 C_{p0}\nu_0}\right]\left[\frac{\nu_0}{L_0 U_0}\right]\frac{\partial^2 T^*}{\partial x_k^* \partial x_k^*} + \frac{\partial < -\theta' u_i' >^*}{\partial x_i^*} + \left[\frac{\nu_0}{U_0 L_0}\right]\left[\frac{U_0^2}{C_{p0}(\Delta T)_0}\right]\phi^*. \tag{23}$$

Each of the independent and dependent variables has been scaled as follows to yield a nondimensional form (designated by the asterisk): $(U_i{:}U_0)$, $(u_i'{:}U_0)$, $(x_i{:}L_0)$, $(t{:}L_0/U_0)$, $(\rho{:}\rho_0)$, $(\Omega_j{:}\Omega_0)$, $(P{:}\rho_0 U_0^2)$, $[\Delta T{:}(\Delta T)_0]$, $[T{:}(\Delta T)_0]$, $[\theta'{:}(\Delta T)_0]$ and $(g{:}g_0)$. If the boundary-layer thermal stratification consists of a lower unstable layer (mixing layer) of thickness H_1 with an upper stable layer of thickness H_2, the foregoing equations can be scaled for each layer. For the lower layer $L_0 = H_1$, $U_0 = (U_0)_1$, $(\Delta T)_0 = [(\Delta T)_0]_1$ and $\rho_0 = (\rho_0)_1$, while for the upper layer $L_0 = H_2$, etc.

One set of requirements for *exact* similarity is equality of the nondimensional coefficients (quantities in brackets) shown in equations (21), (22) and (23) for the physical model and the atmosphere. In summary, the requirements may be stated as follows:

(*a*) Undistorted scaling of geometry
(*b*) Equal Rossby number—Ro $= U_0/(L_0\Omega_0)$
(*c*) Equal gross Richardson number—Ri $= [(\Delta T)_0/T_0](L_0/U_0^2)g_0$. If the atmospheric flow is composed of two layers of different stratification, two Richardson numbers, say Ri_1 and Ri_2, are required to specify similarity requirements.
(*d*) Equal Reynolds number—Re $= U_0 L_0/\nu_0$
(*e*) Equal Prandtl number Pr $= \nu_0/(k_0/\rho_0 C_{p0})$
(*f*) Equal Eckert number—Ec $= U_0^2/[C_{p0}(\Delta T)_0]$

The foregoing requirements must be supplemented by the stipulation that the surface-boundary conditions and the approach-flow characteristics be similar for the atmosphere and its model.

Surface-boundary-condition similarity requires similarity of the following features:

(*a*) Surface-roughness distribution with "aerodynamically rough" behavior,
(*b*) Topographic relief, and
(*c*) Surface-temperature distribution.

Similarity of the approach-flow characteristics requires similarity of the following flow features:

(*a*) Distributions of mean and turbulent velocities,
(*b*) Distributions of mean and fluctuating temperatures,
(*c*) The longitudinal pressure gradient (should be zero), and
(*d*) Equality of the ratio H_2/H_1 if the flow is layered.

If all the foregoing requirements were met simultaneously, all scales of motion ranging from micro to mesoscale, 10^{-3} to 10^5 m, could be simulated within the same flow field for a given set of boundary conditions. However, all of the requirements cannot be satisfied simultaneously by existing laboratory facilities, and partial or approximate simulation must be used. This limitation requires that atmospheric simulation for a particular wind-engineering application must be designed to simulate most accurately those scales of motion which are of greatest significance for the application [5].

Wind Tunnels. A wind tunnel which will meet requirements for simulation of the natural wind must be given special design consideration. The meteorological wind tunnel (MWT) shown in Fig. 13 was designed for this purpose [54, 55]; therefore, the wind-simulation capabilities of wind tunnels are considered in reference to this facility. Basic aerodynamic and thermal characteristics of the MWT are as follows:

(*a*) Air speed (ambient in test section): 0.1–30 m/s (0.3–98 ft/s)
(*b*) Turbulence intensity (ambient in test section): 0.02 percent

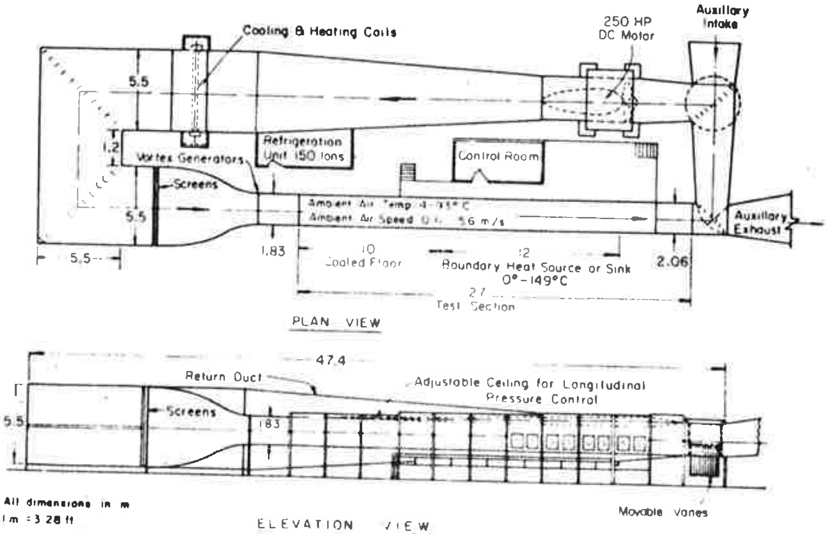

Fig. 13 Meteorological wind tunnel—Fluid Dynamics and Diffusion Laboratory, Colorado State University, Cermak [54, 55]

(*c*) Longitudinal pressure gradient: adjustable to zero by means of an adjustable ceiling
(*d*) Air temperature (ambient in test section): 5–95 deg C
(*e*) Boundary temperature (test-section floor): upstream 13 m (42.6 ft), 1 deg C to ambient; downstream 13 m (42.6 ft), 1–200 deg C

Gross boundary-layer parameters measured by Zoric and Sandborn [131] for a smooth surface and an ambient wind speed of 18 m/s (59 ft/s) are shown in Fig. 14. These measurements show that the boundary layer becomes fully developed at about 10 m (33 ft) from the test-section entrance. Vertical profiles of mean velocity, turbulence intensity and Reynolds shear stress [131] each become similarity distributions for distances beyond 10 m (33 ft) when scaled with the boundary-layer thickness. Accordingly, beyond 10 m (33 ft), the turbulent flow properties for the lower 10–15 percent of the MWT boundary layer exhibit planar homogeneity—a condition which is found in the atmospheric surface layer (also a hypothesis of Monin and Obukhov [38]) for flat, uniformly rough terrain. A disadvantage of wind tunnels with relatively short test sections (less than 10 m) is that, although mean-velocity profiles reasonably similar to atmospheric profiles may be generated by grids, vortex generators, etc., a fully-developed layer with unchanging turbulence properties is not achieved [59]. This is a limiting factor in the use of short test sections for diffusion investigations, but may not be a serious limitation for studies of wind effects on a building.

Boundary-layer thicknesses in the MWT for neutral flow at an ambient wind speed of 10 m/s (33 ft/s) vary with roughness, as shown in Fig. 15 [50]. Mean-velocity and temperature distributions for both stable and unstable thermal stratification measured in the MWT [132] are compared with atmospheric data [133] in Fig. 16. Agreement of both sets of data with the log-linear forms of equations (14) and (15) confirm that the laboratory and atmospheric data are similar. Energy spectra for the longitudinal component of turbulence measured in the MWT at 25 m (82 ft) from the test section entrance behave very much like atmospheric spectra, as shown in Fig. 17 [50]. Other comparisons of mean-velocity, variance of vertical component of turbulence, eddy diffusivities for heat and momentum transfer, and gross-Richardson-number variation with height measured in the MWT with comparable atmospheric data have shown similar behavior in all cases [135, 51, 4].

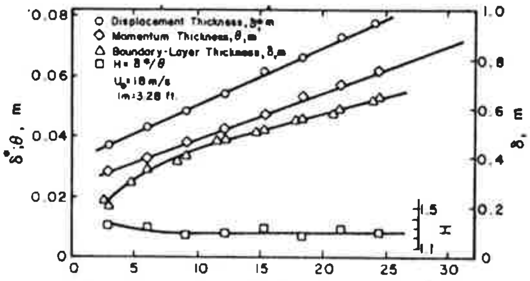

Fig. 14 Mean-velocity profile parameters for meteorological wind tunnel [131]

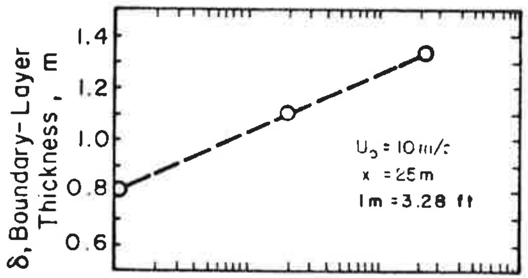

Fig. 15 Boundary-layer-thickness dependence on roughness height in meteorological wind tunnel [50]

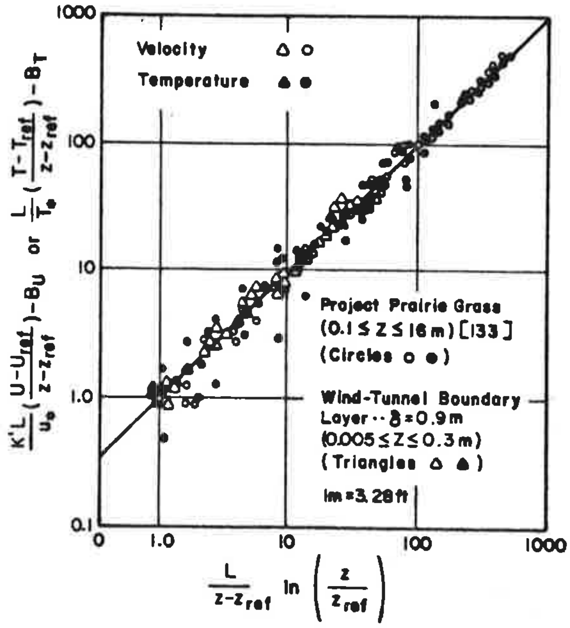

Fig. 16 Mean-velocity and temperature profiles from meteorological wind tunnel and atmosphere compared to log-linear profile

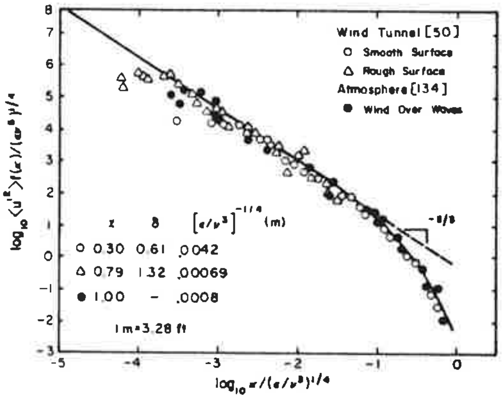

Fig. 17 Energy spectra for longitudinal component of turbulence

Energy spectra for boundary-layer turbulence (Fig. 17) in the MWT can be compared with the energy spectrum of turbulence in the atmospheric boundary layer, given by Fig. 6, to establish the scale range of atmospheric motions simulated under neutral and near-neutral thermal conditions. Fig. 18 summarizes the simulated spectral ranges for model scales ranging from 10^{-3} to 10^{-4} times the prototype lengths, when roughness elements for the full-scale surface have a height h = 20 m (65 ft). The wind-tunnel wave numbers have been converted to frequencies for a 6 m/s (20 ft/s) mean wind speed.

When the length-scale ratio is 10^{-3} nearly all of the scales smaller than the central spectral-gap scale are reproduced. Accordingly, a 1:1000 scale model represents an optimum scaling for air-pollution studies. Scales down to 1:10,000 can be utilized also, but exaggeration of surface roughness becomes necessary for surface roughness elements less than 20 m (65 ft) in height. A scale of 1:10,000 would be used when nonuniformity of mean velocity resulting from extensive topographic features is an important part of the dispersion process. At scales near 1:100, simulation is achieved only down to scales associated with the maximum turbulent energy resulting from local surface roughness. When local diffusion near buildings and building-plume interactions are under investigation, a model scale of approximately 1:100 simulates the important scales of motion.

By considering each similarity requirement separately it is possible to determine for what flow features "exact" similarity between the MWT boundary layer and the atmospheric boundary layer is lacking. Equal *Rossby numbers* are not obtained. This means that turning of the mean wind direction with height is not simulated. Accordingly, the MWT boundary layer is an adequate model for atmospheric flow when either this effect is not significant for the application, or the turning is small (flow not in equilibrium with Coriolis force and other forces), which Hoxit [100] suggests may be a large part of the time. Equal gross *Richardson numbers* can be obtained. Gross Richardson numbers over a layer 0.1 m (0.3 ft) thick above the surface can range from −0.5 to 0.5 in the MWT. This covers a wide range of atmospheric conditions and is an essential feature for application to diffusion investigations.

Equal *Reynolds numbers* are not attainable. However, this does not seriously limit capabilities for modeling the atmospheric boundary layer—the significant flow characteristics are weakly dependent upon the Reynolds number. This is illustrated by Fig. 19, in which the total surface drag coefficient for a given ratio of boundary length to roughness length L_0/K_s becomes invariant with respect to the wind-tunnel Reynolds number U_0L_0/ν well within the MWT Reynolds-number range. Since essentially all natural surfaces are "aerodynamically rough," flow structure related to momentum transfer will be similar (at least within the wall region) if the scaled-down roughness has a sufficiently small value for L_0/K_s, as determined by Fig. 19. Should the resulting L_0/K_s be too large, the roughness heights can be exaggerated to produce an "aerodynamically rough" surface.

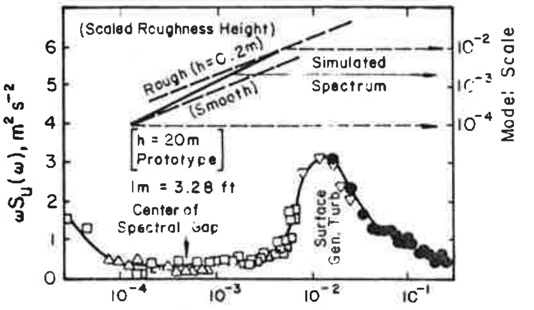

Fig. 18 Range of spectrum simulated in meteorological wind tunnel for different model scales, when prototype roughness elements are 20 m (65 ft) high

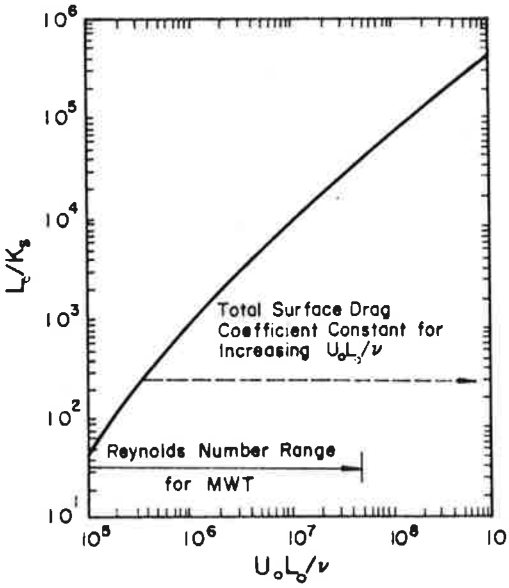

Fig. 19 Wind-tunnel Reynolds number U_0L_0/ν at which total surface drag coefficient becomes constant for a specified surface length-roughness length ratio L_0/K_s [136]

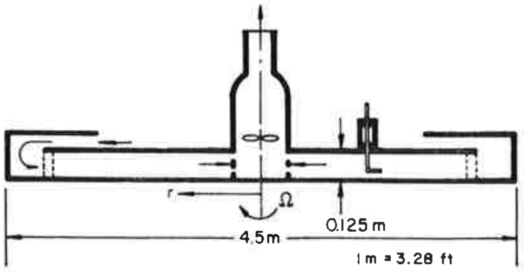

Fig. 20 Rotating flow facility of Caldwell and Van Atta [144]

The *Prandtl numbers* are essentially equal for flows in the MWT and the atmosphere. *Eckert numbers* are not equal when equal Richardson numbers are achieved. This compromise with exact similarity has not been found to have measurable effects on similarity of the wind characteristics—an expected result since the Eckert number is equivalent to a Mach number squared, which is small compared to unity for both laboratory and atmospheric flows.

Surface boundary conditions can usually be met if adequate care is taken. Surface roughness is scaled in accordance with the prototype roughness; however, when this results in an aerodynamically smooth surface the roughness-element heights must be increased by an increment equal to the viscous-zone thickness—10 ν/u_*. Additional research is needed to determine if this roughness modification results in satisfactory simulation of the flow structure.

Surface temperature distributions are obtained by the addition of heating and/or cooling elements as part of the boundary [54] to generate uniform-temperature or temperature-gradient distributions. A network of surface heating elements can be designed to reproduce even complex distributions, such as an urban heat island [137].

Approach-flow characteristics which adequately simulate the winds immediately upstream from a small-scale power plant or a tall-building model to be used to study plume downwash or wind forces, respectively, can be simulated. The MWT permits all of the mean and turbulence properties of temperature and velocity to be simulated by the same processes active in an atmosphere. However, the surface transfer processes may be supplemented by grids, steps, jets, or vortex generators at the test-section entrance to stimulate growth of the boundary layer. Much research is being devoted currently to evaluation of these various methods, especially for short-test-section wind tunnels [59, 138, 139, 140, 141, 142, 143]. Most of the investigations produce a common result—roughness downstream of the generating system should be matched to the mean-velocity profile generated if that profile is to be maintained downstream.

Other Flow Systems. A variety of laboratory facilities have been designed to investigate special features of motion in the planetary boundary layer. Space permits only brief descriptions of several systems which show promise for more intensive application to wind-engineering investigations.

Caldwell and Van Atta [144, 145] constructed the *rotating flow facility* shown in Fig. 20 for the purpose of investigating in-

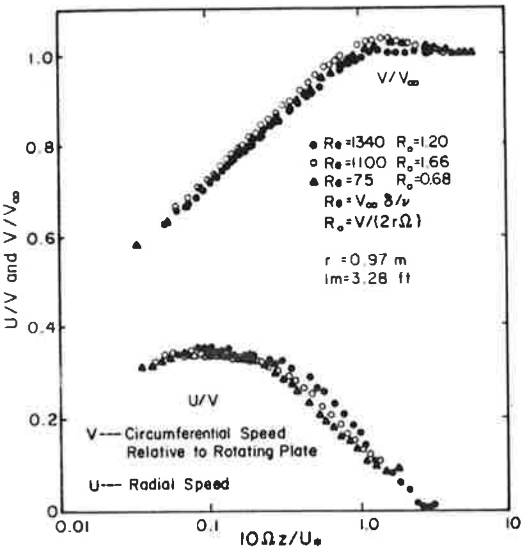

Fig. 21 **Mean velocities in turbulent Ekman boundary layer measured by Caldwell and Van Atta [144]**

stabilities of the laminar Ekman boundary layer. The laminar boundary layer produced was found to have the same form as predicted by the analysis of Ekman [146], and confirmed findings of Faller [147] on critical Reynolds numbers for instability which were obtained in a smaller rotating basin. However, the larger Reynolds number capability of the facility shown in Fig. 20 produced a well-developed turbulent Ekman boundary layer. The mean-velocity measurements made in this layer are shown in Fig. 21 and reveal gross characteristics similar to those for the planetary boundary layer shown in Fig. 1. This flow could be used to investigate the effect of wind direction change with height on flow over a tall building, which is now assumed to be negligible. Application to diffusion investigations for air-pollution control may be possible with a modified facility of this type; however, much more study of the flow system will be required.

A *water channel* used by Clark [56] to investigate stability of stably stratified shear flows is sketched in Fig. 22. In this case only flow for a small region of the boundary layer was simulated —one stably-stratified layer. Further development of water channels for simulation of the entire planetary boundary layer in much the same manner as the wind tunnel would provide two attractive features—a 10-fold increase in Reynolds number for the same size facility, and good opportunities for flow visualization by the hydrogen-bubble technique. On the other hand, disadvantages arise due to greater difficulty with turbulence measurements and substantial operational costs for stratification.

Wind-water channels have been developed to investigate the interaction of wind with water surfaces—heat, mass and momentum transfer. The largest and most sophisticated facility of this type has been constructed in Marseille, France [58]. The aerodynamic working section is 40 m (131 ft) long, 3.20 m (10.5 ft) wide and 1.45 m (4.75 ft) from the water surface to the upper boundary; the hydraulic working section is 2.6 m (3.5 ft) wide with a depth ranging from 0.75 m (2.46 ft) to 1.0 m (3.28 ft). Wind speeds range from 0.50 m/s (1.64 ft/s) to 14 m/s (46 ft/s). Temperature of the air and water are controlled independently and can be varied between 5 deg C and 40 deg C. Boundary-layer thickness and Reynolds number variation are shown in Fig. 23, and the variation of a gross Richardson number for a layer 0.25 δ is shown in Fig. 24. The range of these parameters makes this wind-water channel a useful facility for wind-engineering investigation of local diffusion around offshore structures, and for both wind and wave forces on such structures.

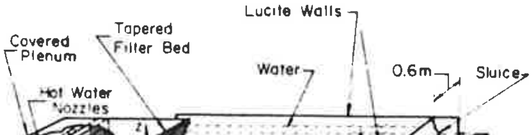

Fig. 22 **Water channel used for stability investigation of stably stratified shear layers by Clark [56]**

Although several serious attempts have been made to develop a *tornado-simulation facility*, the capability for simulating this important atmospheric phenomenon remains in a primitive state. Chang [148] and Ward [149] have developed tornado-like vortices by moving air over a ground board by means of a ducted fan centered above the board. Rotary motion is imparted to the air by a rotating screen in the form of a circular cylinder near the ground-board periphery and co-axial with the fan centerline. Hsu [150], on the other hand, used a ducted fan to move air over a rapidly rotating honeycomb, through a contraction, and thence downward against a ground board as shown in Fig. 25. A strong upward moving core is developed for certain combinations of flow and rotation rates. Both methods develop flow characteristics which resemble air motion in the tornado. More knowledge on air motion in a tornado and detailed measurement of flow structure in the laboratory-generated vortices are required

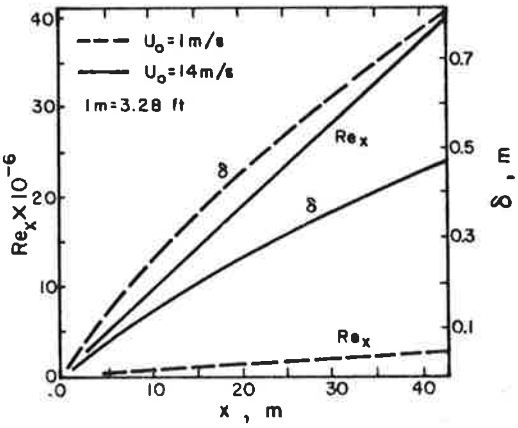

Fig. 23 **Reynolds number U_0x/ν and boundary-layer thickness for wind-water channel—Coantic, Bonmarin, Pouchain, and Favre [58]**

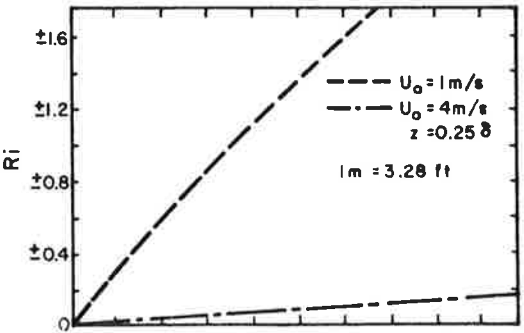

Fig. 24 **Bulk Richardson number over lower layer 0.25δ thick for wind-water channel—Coantic, Bonmarin, Pouchain, and Favre [58]**

before a reliable model for wind-engineering investigations can be established.

Summary of Research Needs. The long-test-section, low-speed wind tunnel has been shown to have a capability for simulation of atmospheric-boundary-layer features essential for wind engineering. As a result, this type of wind tunnel can be utilized for fundamental research to relate theory to practice as well as to provide data for design and planning of specific engineering projects. The scope of studies possible in a wind tunnel of this type can be increased. Systematic research to determine the way in which turbulence characteristics are related to surface-roughness features and development of a system to increase the energy of large-scale turbulence are needed, if expanded applications of the wind tunnel are to be realized.

Simulation of the atmospheric boundary layers in wind tunnels with short test sections (length less than about six times the minimum cross-section dimensions) remains to be accomplished in a reliable manner. Development of a satisfactory combination of boundary-layer stimulators and surface roughness for the purpose is badly needed, but will require considerably more research than has been accomplished to date.

The conventional wind-engineering wind tunnel does not simulate the effects of Earth's rotation on the atmospheric boundary layer. Development of a flow facility to simulate the change in mean wind direction with height is needed.

A most urgent need is development of a flow facility to simulate tornadoes. High priority should be given to research in such facility which will define conditions necessary for formation of "suction vortices" and to check the flow structure of a tornado predicted from various analytical studies.

Further development of wind-simulation capabilities must be accompanied by comparisons of laboratory and field data. Therefore, the field-measurement program recommended to establish wind characteristics should be designed to provide data for wind-model confirmation. The meteorologist and fluids engineer must communicate continuously for this to happen.

5 Atmospheric Advection and Dispersion of Air Pollutants

Wind engineering includes many applications in which the transport and mixing of gaseous or particulate materials by the atmosphere may have a significant influence on decisions related to the overall planning, design details or operational strategy for public and private project developments. Ground-level concentrations of effluents released from stacks, automobiles, air-conditioning exhausts, nuclear power-plant vents and many other sources must be kept below levels which may be harmful to man, animals and plants. These sources may be found in isolation and surrounded by long reaches of flat uniformly rough surfaces (the classical setting), or near large structures which are surrounded by a variety of surface obstacles and non-uniform topography (the complex setting). The engineer, quite often with the cooperation of a meteorologist or climatologist, is called upon to predict dispersion characteristics, primarily on a local scale (within a few kilometers of the source) and most frequently in a complex setting. Long-range predictions of concentrations have been, and remain, an important function of the meteorologist.

The Classical Setting. Applications of fluid mechanics to dispersion in this setting have been highly successful in yielding results for prediction of concentrations. For passive sources, at ground level or elevated within the atmospheric surface layer, Lagrangian similarity concepts enable maximum ground-level concentrations to be predicted when the source strength Q, stability (Monin-Obukhov length L) and surface-roughness length z_0 are known [151, 152]. For example, when the nondimensional maximum ground-level concentration χ_{cp} for a continuous point source is expressed as a power m_{cp} of the dimensionless downwind distance; i.e.,

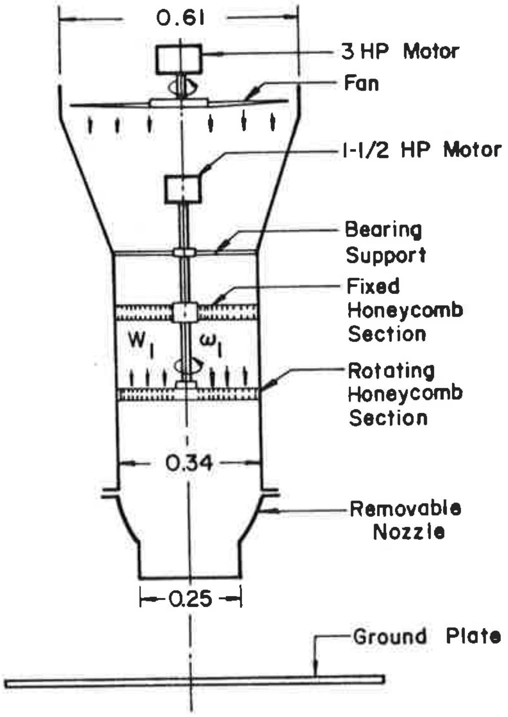

Fig. 25 Tornado-core simulator developed by Hsu [150]

$$\frac{\chi_{cp} u_* z_0^2}{Q} = \text{const } \xi^{m_{cp}} \tag{24}$$

the power m_{cp} is found to be the following [151]:

$$m_{cp} = \frac{-bk'\xi}{\zeta.}\left\{\frac{2\log\zeta + \alpha(\zeta - 1) + \alpha\zeta + 1}{[\log\zeta + \alpha(\zeta - 1)][\log\zeta + \alpha(\zeta + {}^1/_4\zeta\log\zeta - 1)]}\right\}. \tag{25}$$

Equations (24) and (25) are related, through $\zeta = \bar{z}/z_0$ and $\xi = x/z_0$, for small values of α by the following equation:

$$bk'\xi = (\zeta\log\zeta - \zeta) + \alpha\left(-\zeta + \frac{7}{16}\zeta^2 + \frac{1}{8}\zeta^2\log\zeta\right) - (H\log H - H) - \alpha\left(-H + \frac{7}{16}H^2 + \frac{1}{8}H^2\log H\right) + bH\,[\log H + \alpha(H - 1)]. \tag{26}$$

In these expressions $b = 0.4$ (Batchelor constant), $k' = 0.4$ (Kármán constant), $\alpha = z_0/L$, $H = h/z_0$ and $\bar{z}$ is the elevation of the plume center-of-gravity. The significant fluid-mechanical feature of this formulation is that the roughness length z_0 determines the scale for the dispersion process.

After formulation of equation (26) and a similar equation for a continuous line source, Cermak [151] used them to compare concentration data measured in the laboratory and in the field. Data from the meteorological wind tunnel and from field studies in Nebraska [133] were found to follow the predicted decay rates. This agreement not only supports the validity of Lagrangian similarity but reveals similarity of turbulent diffusion processes in the turbulent boundary layer of the meteorological wind tunnel and the atmospheric surface layer.

Much attention has been given to the description of buoyant, elevated plumes. Of particular interest is the rise of a plume, Δh, above the top of a stack—a phenomenon which is complicated by being dominated initially by momentum of the effluent, and finally by its buoyancy. Briggs [153] reviewed the multitude of formulae proposed for this purpose by comparing predictions with field data on plume rise. He concluded that the expression

$$\Delta h = 1.6\, F^{1/3}\, U^{-1} x^{2/3} \tag{27}$$

is a good representation for all stratifications, but the distance over which equation (27) is valid depends upon the stratification. In this expression F, a buoyancy-flux parameter, is given by

$$F = \frac{gQ_H}{\pi C_p \rho T} . \tag{28}$$

A somewhat similar gross—approximation formula resulted from the investigations of Fay and his associates [154]

$$\frac{\Delta h}{1_b} = 1.32 \left(\frac{x}{1_b} \right)^{2/3} \tag{29}$$

where 1_b is a buoyancy length given by

$$1_b = \frac{gQ_H}{\pi \rho C_p T U^3} \tag{30}$$

and the range of x is limited.

Both (27) and (29) have the characteristic $x^{2/3}$ behavior for buoyancy-dominated motion, and the initial effects of momentum domination are included to give a gross buoyancy effect. These forms are of great practical value in estimating the average plume rise over a period of time for a given stack and operating mode. The initial momentum-dominated plume rise may be treated separately, as shown by Csanady [155], to give a $x^{1/3}$ dependency. This is in good agreement with observations for a zero density-difference jet emitted into a cross flow [156]. Laboratory data on the behavior of stack gases with negative buoyancy are presented by Hoot and Meroney [157].

Estimation of ground-level concentration downwind from a source of effective stack height H_s (stack height plus maximum plume rise) requires a working model for atmospheric diffusion. The most elementary and widely used formulation is developed from the gradient-transport or K-theory model. This leads to the Gaussian plume for which ground-level concentrations are given by

$$\chi(x, y, D, H_s) = \frac{Q}{\pi \sigma_y \sigma_z U} \exp - \frac{1}{2}\left[\left(\frac{y}{\sigma_y} \right)^2 + \left(\frac{H_s}{\sigma_z} \right)^2 \right] . \tag{31}$$

Equation (31) has formed the basis of several useful guides for estimating pollutant concentrations [158, 159, 160]. In the classical setting, this formulation gives reasonably accurate predictions when appropriate values of σ_y and σ_z for the surface roughness and thermal stability are selected. Unfortunately, (31) has been used in attempts to predict concentrations in complex settings where the mean flow is no longer unidirectional and usually not defined.

A new approach under development which leads to atmospheric-dispersion estimates in the classical setting is the method of invariant modeling. Donaldson [161] has performed numerical integrations on a set of equations formulated from the Reynolds equations of motion, the turbulent transport equation, and a set of closure relationships between various second-order correlations. The closure relationships remain open to question, and will remain so until a clear understanding of turbulence emerges. Concentrations were computed for a line and a point source; however, much more fundamental research on the model is required before it can be used as an engineering tool.

The Complex Setting. Dispersion in regions near a source where the flow is distorted by buildings, structures and topographic features large compared to the plume diameter within and near the region of interest may be called a complex setting. Within the scope of this setting is the downwash of stack effluents associated with downward wind velocities produced by separation and vortex formation, recirculation of effluent discharged from building vents into ventilation intakes, and entrapment of automobile emissions and parking-garage exhaust discharges in city street canyons—a few of the many current environmental problems. At this time physical modeling of atmospheric dispersion is necessary to obtain pollutant-concentration information for proposed modification to existing facilities [162, 163] and for new facilities or urban developments still in the planning stage [164, 165, 166, 167].

Simulation of atmospheric dispersion requires not only that the atmospheric boundary layer be simulated, as described in Section 4, but that the material being dispersed must satisfy certain similarity conditions also. Similarity conditions for gaseous effluents have been discussed by Strom and Halitsky [168], Lord and Leutheusser [169] and Meroney, Cermak, Garrison, Yang and Nayak [170]. Three dimensionless ratios have been found by dimensional arguments and analytical developments to be sufficient for specifying similarity—

1 Ratio of stack gas efflux speed to mean wind speed at level of discharge, V_G/U_s
2 Froude number for gaseous discharge, $\rho_a U_s^2/[(\rho_a - \rho_s)gD]$
3 Internal Reynolds number, $V_G D/\nu$

where D is the internal stack diameter and $\rho_a - \rho_s$ is the difference in density of the local atmosphere and the discharged gas. A fourth dimensionless ratio $(\rho_a - \rho_s)/\rho_a$ should be made equal in model and prototype for exact similarity. This requirement has been relaxed by investigators on the grounds that the ratio is very small for the usual cases found in practice. However, this ratio in the laboratory is often two to three times larger than atmospheric values. A systematic study is needed to determine the significance of this ratio on plume behavior.

The specific-weight difference is achieved in the laboratory most easily by using an air-helium mixture. The helium may be used as a tracer gas to determine concentrations over the model [171], or a radioactive tracer gas such as Krypton 85 [172] may be used for this purpose. The commonly used modeling scales of from 1:100 to 1:500 require very low values of U_s if the Froude numbers are to be made equal. By making $\rho_a - \rho_s$ two to three times larger than for the atmosphere, U_s can be increased to about 0.5 m/s (1.6 ft/s). Equality of the internal Reynolds number cannot be achieved; however, by roughening the inner surface of the discharge duct a turbulent exhaust flow may be developed.

When particulate matter is also released into the atmosphere the particles p must be selected to make U_s/U_f (U_f is the terminal speed of the particle) and $\rho D_s/(\rho_p D_p)$ equal to the prototype values for similarity of motion while suspended. Since the particles are distributed in size, U_f should be interpreted as the fall velocity for the mean-diameter particle, and the particle-size distribution should be made similar to the prototype distribution. When the particles have reached the surface, similarity of motion requires that U_f/u_{*t}, $\rho D_s/(\rho_p D_p)$ and $u_{*t} D_p/\nu$ each be equal to prototype values [173, 174]. The shear velocity u_{*t} is the threshold value required to initiate particle motion.

One additional concern is that the flow over local objects, such as buildings near the source, be similar to the full-scale flow. Halitsky [175] reports that an investigation by J. Golden revealed that the separation cavity and vortex structure for a building becomes fixed in form for building Reynolds numbers in excess of 11,000—a value which can usually be exceeded if the model scale is not less than about 1:400.

Downwash of gases emitted from stacks has been, and continues to be, a difficult problem to solve in an economical manner. The problem is complicated by the development of a downward motion in the lee of a building, as shown in Figs. 26 and 27,

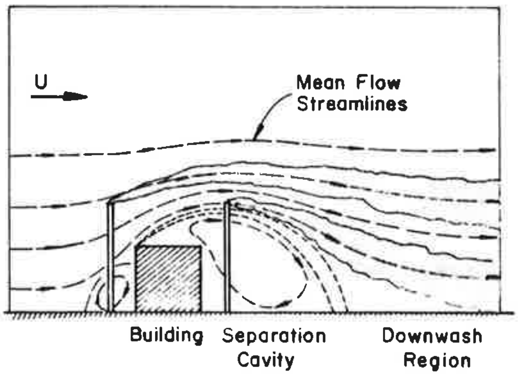

Fig. 26 Downwash resulting from flow disturbance by a single building

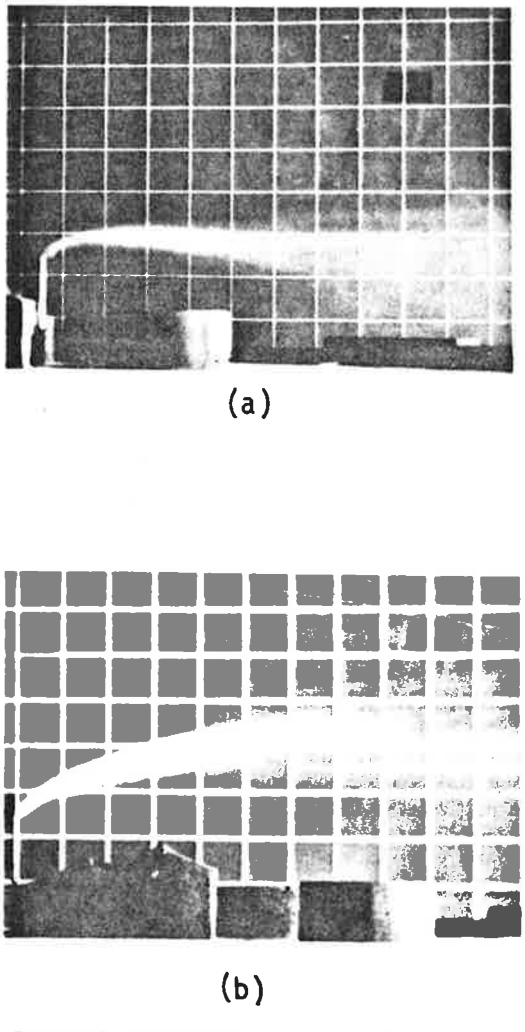

Fig. 27 Downwash visualization by smoke emission from a small scale: (*a*) stack downwind of building, (*b*) stack upwind of building

which depends upon geometry of the building, wind direction and the presence of other nearby obstacles. A variety of downwash problems caused by buildings and topography are illustrated in [158, 159, 160]. Development of a general description of this flow has not been achieved; therefore, the practice of making a model study for individual plants, started by Sherlock and Stalker [34, 176], continues to be common. Laboratory techniques now in use [162, 169, 171, 172, 177, 178] yield pollutant concentrations such as those shown in Fig. 28. Information of this type, together with local climatological data, enables a stack height and location to be selected to give ground-level concentration which will not exceed standard values set by regulatory agencies. In general, ground-level concentrations for a given wind direction and plant operating level increase with increasing wind speed. This is because the flow pattern of Fig. 26 does not change materially, so that as the initial plume trajectory approaches the horizontal it eventually moves downward on a steeper streamline. When additional structures are nearby, the flow, of course, becomes much more complex [179].

Material discharged near the surface of a building, either through a vent or an unintentional leak, may pollute air over a large portion of the building surface. Since very little work has been done to define flow in boundary layers and separated regions of bluff bodies [180], pollutant concentrations over a building surface must be determined by measurements on a small-scale model placed on a simulated atmospheric boundary layer [159, 165, 181].

City planners, architects, engineers and environmentalists have a variety of responsibilities in the development of new population centers and the redevelopment of areas within existing cities. One common responsibility which has received much attention in recent years [182, 183, 184] is the social and moral requirement that air-pollutant concentrations will not exceed specified standard levels and that excessive winds leading to human discomfort will be minimized. Little hope exists for describing flow over such complex geometry with sufficient detail to meet this responsibility. Therefore physical modeling of winds and dispersion in proposed urban developments has been utilized to obtain the kinds of quantitative information required.

A model used for planning and design of an urban center is shown in Fig. 29. The multipurpose investigation included measurement of concentrations resulting from automobile-exhaust discharge from a large underground parking garage. Fig. 30 illustrates typical concentration distributions developed by discharge from proposed short stacks within the center. The dispersion of automobile exhausts in city street canyons is currently being studied for systematic changes in city geometry by Cermak, Lombardi and Thompson [185] and Hoydish, Griffiths and Ogawa [186]. The concentration distribution shown in Fig. 31 is affected very strongly by circulation generated within the slot (street canyon).

For the time being at least, application of fluid mechanics to local dispersion over individual buildings and in complex urban areas will be primarily through the application of physical modeling. However, attempts are being made to predict concentration distributions for some of the simplest cases by numerical simulation. Lavery, Egan, and Iwanchuk [187] have performed a numerical study of plume advection and dispersion downwind of

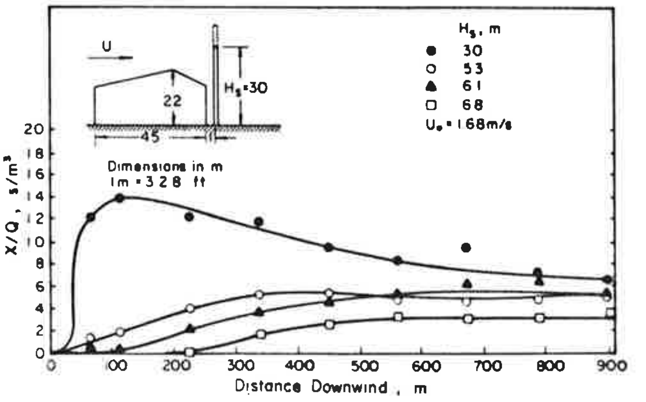

Fig. 28 Effect of stack height *H*$_s$ on ground-level concentration x/Q in downwash region

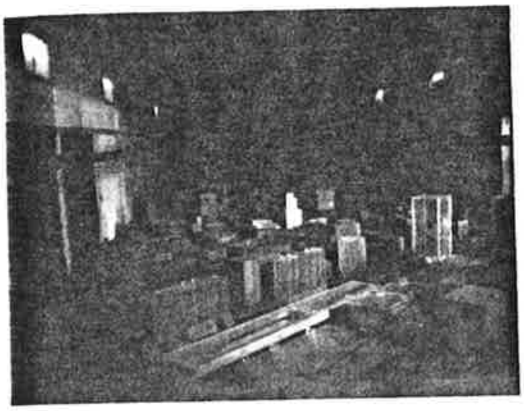

Fig. 29 Model of proposed Yerba Buena Center, San Francisco, (1:240 scale) [164]

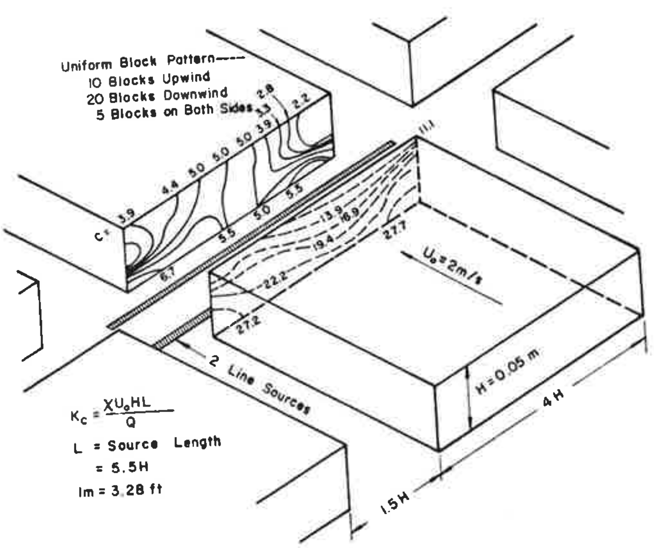

Fig. 31 Concentration distribution in a street canyon for two lanes of traffic [185]

an isolated two-dimensional building. Basic inputs to the numerical model were wind-field parameters determined from wind-tunnel measurements. Analytical refinements of the statistical theory of turbulent diffusion by Hunt and Mulhearn [188] enable turbulent dispersion over two-dimensional obstacles to be estimated. The Lagrangian theory predicts mean-square dispersion of the plume about the mean streamline through the source; however, the basic flow pattern is accessible only through laboratory measurements.

Prediction of atmospheric dispersion over topographic features under strong wind conditions may be accomplished by physical modeling, as described under Section 4. Wind fields for isolated topographic features—Rock of Gibraltar [33, 189] and Bayview Hill, San Francisco [190]—have been simulated with good accuracy in the wind tunnel on scales of 1:5000 and 1:800, respectively. Atmospheric advection over extensive complex mountainous areas at scales down to 1:15,000 has been simulated successfully for stably stratified flows with no radiational heating of the land surface [5, 191, 192]. For this case the laboratory flow becomes laminar, and similarity results from the atmosphere behaving as a very viscous fluid with a viscosity of K_m [4]. Lin, Liu, and Pao [193] investigated the effect of stable stratification on plume behavior for flow over an idealized mountain. The laboratory study was performed by towing a model of the mountain and stack (mounted upside down on a carriage) through a tank of water stably stratified by addition of salt. Plume behavior was observed to be quite similar to what has been observed in the atmosphere.

Dispersion in mountain-valley wind systems resulting from diurnal heating cycles is not known to have been described by any method. Buettner and Thayer [194] after a comprehenisve study of valley winds in the Mount Rainier area conclude the following: "There is neither a perfect valley nor a perfect gradient wind-free weather condition; there will never be enough synoptic three-dimensional observations in order to show all parts of a valley wind system clearly. The best we can do is to establish a model of happenings under ideal conditions." Description of this class of flow systems (a problem of great practical importance) presents an outstanding challenge for imaginative use of fluid mechanics in the development of a reliable physical model.

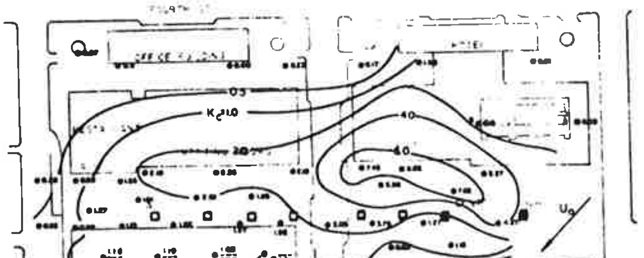

Fig. 30 Concentration coefficients K_c in Yerba Buena Center, San Francisco [164]

Summary of Research Needs. Atmospheric diffusion for the classical setting is understood sufficiently for most wind-engineering purposes. However, continuous fundamental research is needed to develop a basic formulation for turbulent diffusion which will represent the physical processes involved, and also provide an efficient engineering tool.

Physical modeling is currently relied upon to predict advection and dispersion of air pollutants in a complex setting. This technique could be made even more useful to wind engineers by research on the following questions:

(*a*) At what Reynolds number does stably stratified flow of a specified Richardson number over a small-scale model of an industrial building cease to be similar to the prototype flow?

(*b*) What modeling procedure should be used to simulate mountain-valley winds caused by nonuniform solar heating of Earth's surface?

(*c*) How large can the density ratio $(\rho_a - \rho_s/)\rho_a$ be, for effluent from a small-scale power-plant stack, without causing significant deviations from plume similarity?

(*d*) How can turbulent concentration fluctuations and time-dependent concentrations in unsteady systems be measured accurately?

Physical modeling of advection and dispersion using a wind tunnel with capabilities similar to those of the meteorological wind tunnel described in this review can yield very useful data through systematic investigations. In particular, investigations to provide the following information would be of great value to wind engineers:

(*a*) The relationship between geometrical parameters, stack-gas parameters, and meteorological factors on downward characteristics in the vicinity of industrial-plant buildings and topographic features,

(*b*) Appropriate forms for diffusion coefficients in flow over complex urban areas,

(*c*) The relationship between city-canyon geometry and automobile-exhaust-gas concentrations within the canyon, and

(*d*) The effect of building geometry and surrounding buildings on circulation of air pollutants over the building when they are released at the building surface.

These and many other similar bodies of data may be obtained in the laboratory. However, a carefully planned field study of dispersion near a building should be coordinated with a model study. This is needed to establish the relationship between mean concentrations measured in the laboratory and in the field for different sampling times.

6 Wind Forces

Even though wind forces on buildings and structures have been a subject of concern for the past 200 years, as shown in the Historical Summary (Section 2), the fluid mechanics related to this area of wind engineering is not well understood. Unlike the aerodynamics of stream-lined bodies which is highly developed for aeronautical applications, the aerodynamics of bluff bodies in turbulent shear flows involves the nonlinear interaction of nonhomogeneous, nonuniform, turbulent approach flow with three-dimensional turbulent boundary layers and separated flows over the body—none of these complex flow types are well described even when unperturbed by the others [180]. Consequently, the available wind-force information for buildings and structures has been obtained primarily from measurements on small-scale models and on actual structures, as indicated in a review by Scruton [195].

Wind forces of primary concern to the structural engineer and architect may be classified in three broad categories as follows:

(*a*) Time average of pressures

(*b*) Instantaneous local values of pressures

(*c*) Instantaneous surface-integrated pressures (unsteady forces)

The time-averaged pressures give overall quasi-steady state moments and shears when integrated over the entire building surface. This type of information is used for "static" design purposes. The instantaneous local values of pressure are essential for proper selection of glass lights and cladding. Instantaneous surface-integrated pressures produce unsteady loading which leads to dynamic response of the structure. The types of response depend upon the nature of the unsteady forces and have been classified as vortex excitation, galloping excitation, gust or buffeting excitation, stall-type flutter and classical flutter. Because instantaneous pressure distributions over the surface of a structure are inaccessible, unsteady-loading phenomena have been studied primarily by observing dynamic response of the structure.

The three broad categories of wind forces will be reviewed briefly in the following paragraphs. Whenever possible, needs for specific research in fluid mechanics to better understand either the nature of these forces or their simulation are identified.

Time Average of Pressures. Time-averaged pressure differences are used to determine mean moments and shears for the design of stiff or highly damped structures. Mean-pressure coefficients are formed from a mean pressure difference divided by a dynamic pressure based on a mean reference wind speed—$\overline{C}_p = \overline{\Delta p}/(\rho U_g^2/2)$. The averaging time must be considered carefully, both in the acquisition and use of mean-pressure coefficients. Wind-tunnel averaging time of about 15s [196] and fullscale averaging time of about 500s [86] result in stable averages. Both averaging times correspond to velocity-fluctuation periods within the spectral gap shown in Fig. 18.

A reference pressure p_{ref} must be selected when measuring the mean pressure difference $\overline{\Delta p} = \overline{p - p_{ref}}$. In the wind tunnel p_{ref} is well defined by the customarily used undisturbed pressure at a substantial distance above the building model. However, when mean pressure differences are determined from measurements on full-scale structures, no comparable reference pressure is available [86]. Use of a near-absolute-vacuum pressure reference can eliminate the problem of internal reference-pressure changes due to stack effects or operation of air-conditioning equipment, and external pressure influences transmitted by ducts or cracks through exterior walls. However, the vacuum reference results in the pressure difference between the reference and the building-surface pressure being large compared to pressure differences for various points on the building surface. The measured pressure difference also includes barometric pressure changes. This is a problem which requires more careful study if meaningful comparisons of wind-tunnel and full-scale pressure measurements are to be made. The geostrophic wind speed U_g is taken as the mean free-stream wind speed in the wind tunnel. In the full-scale case, U_g must be determined from wind measurements at some convenient height that are then related to U_g by the power-law wind profile (10), after selection of an appropriate value of $1/n$ from Fig. 3.

The pressure measurments by Jensen [62] and Dalgliesh [86] indicate that mean pressures on small-scale models of sharp-edged buildings in appropriate boundary layers closely represent full-scale values even though the model Reynolds number may be 100–500 times smaller than the prototype Reynolds number. The same cannot be said for building surfaces which are gradually curved—the circular cylinder in particular. The surface of small-scale models may be roughened to develop separated regions and pressure distributions corresponding to a higher equivalent Reynolds number on a smooth circular cylinder [197]. Armitt [198] concluded from pressure measurements on a model cooling-tower that use of a roughness Reynolds number of about 10^3 will enable approximation of full-scale pressure distributions with sufficient accuracy for engineering purposes. However, in order to determine if pressures such as the peak suction measured at a model Reynolds number of about 10^5, shown in Fig. 32, are satisfactory for a full-scale Reynolds number of 10^8, measurements on the full-scale structure are required. Vickery [199] found that the peak-suction or base pressure for a long square cylinder is strongly dependent upon turbulence of the free stream. Although the points of separation are fixed by the corners, reattachment appears to depend upon the turbulence characteristics—an effect not predictable by any current analysis. Data of the type obtained by Vickery strongly reinforce the requirement that measurements of pressure and the aerodynamic response of tall structures be made in boundary layers which have turbulence characteristics consistent with the surrounding geometry. This can be achieved conveniently by a model such as shown in Fig. 33.

Structures associated with nuclear power plants are currently being designed to withstand winds resulting from passage of a tornado over the site. These wind fields, shown in Figs. 11 and 12, vary greatly over distances comparable to the building size; therefore, the available pressure coefficients obtained for two-dimensional boundary-layer flow over a structure are not applicable. Initial attempts like those of Chang [148] to obtain pressure coefficients for vortex-flow over structures are in urgent

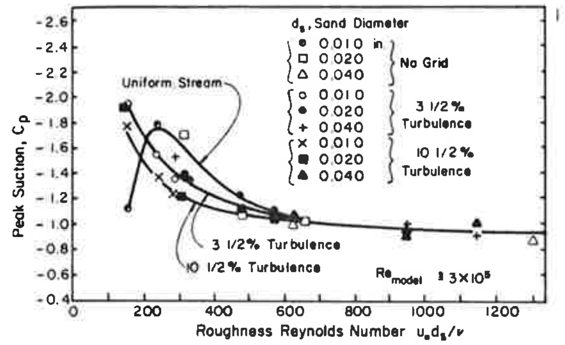

Fig. 32 Effect of surface roughness and turbulence on peak suction coefficient for throat of a circular cooling tower—Armitt [198]

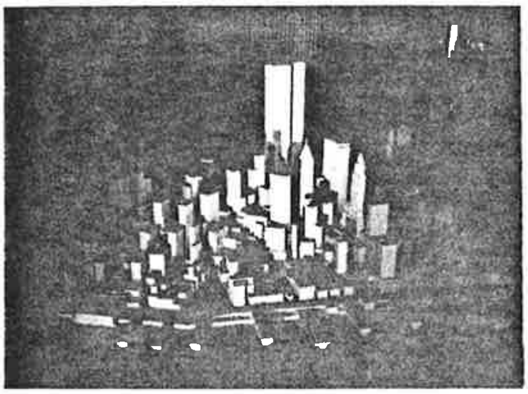

Fig. 33 World Trade Center Towers, New York (1:500 scale) in meteorological wind tunnel shown in Fig. 13

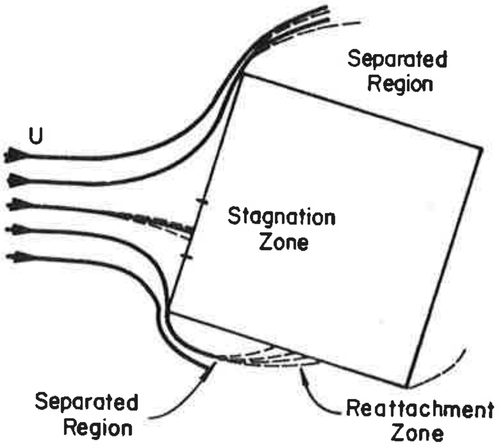

Fig. 34 Flow separation over a building of square cross section

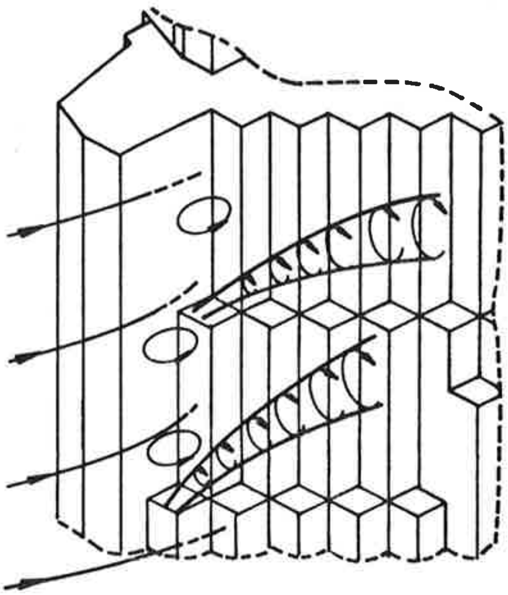

Fig. 35 Vortex formation on surface near corner of Bank of America World Headquarters Building [200, 201]

need of further developments. New types of vortex-generation facilities such as the one shown in Fig. 25 should be evaluated for possible wind-engineering applications.

Instantaneous Local Values of Pressure. The magnitude of instantaneous wind-pressure fluctuations on the exterior surface of a building often exceeds the dynamic pressure of the mean geostrophic wind $\rho U_g^2/2$. The resulting pressure differences across the outer "skin" over areas of 1–10 m^2 (10–100 ft^2) and larger can cause much damage in the form of cladding-panel fatigue failure, glass-panel breakage, panel-anchor failure, and moisture penetration through construction joints. Maximum-peak pressure fluctuations have been associated with the following flow mechanisms [79, 200]:

(*a*) Separation and reattachment of flow around buildings—Fig. 34

(*b*) Local vortex formation by exterior architectural features and vortex action on adjacent surfaces—Fig. 35

In regions of separation, negative values of the peak pressure-fluctuation coefficients C_p' attain magnitudes of 8–10 times the rms-pressure coefficient $C_{p_{rms}}$ quite frequently, as shown by Peterka and Cermak [81] in Fig. 36. On the other hand, C_p' on upwind surfaces (positive C_p) such as the stagnation zone of Fig. 3 follows a Gaussian distribution, as does positive C_p' for separated regions. The pressure-fluctuation spectra for upwind faces have been found to be related closely to turbulence spectra for flows approaching the building [202]. Accordingly, pressure fluctuations on these faces are especially sensitive to flow disturbances (wakes and vortices) developed by upwind buildings and other obstacles.

Pressure-fluctuation data for surfaces of buildings under design can be obtained only by measurements on models in wind tunnels. Roshko [203] points out that blockage effects may contribute the greatest uncertainty in the relationship between pressure coefficients obtained in the wind tunnel and full-scale values. The position of reattachment shown in Fig. 34 could be especially sensitive to such effects. Standen, Dalgliesh and Templin [204] state that pressure fluctuations may be affected by boundary-layer formation on some of the surfaces, and suggest that careful attention should be given to invariant modeling of local flow patterns. They suggest further that this may possibly be accomplished by exaggerating the height of surface-roughness elements such as mullions. The good model-prototype agreements of rms-pressure coefficients found by Dalgliesh [86] indicates that the foregoing modeling problems were not of major consequence for the particular wind-tunnel model used in his investigation.

Instantaneous Surface-Integrated Pressures (Unsteady Forces). Instantaneous distribution of wind pressures on a building yield forces which either vary randomly with time or have a periodic component superimposed upon a random variation. In either case, the structural response is ordinarily a displacement which is random, and a periodic component corresponding to the natural period of the structure. If, in the second case, the periodic wind-pressure force is sufficiently large compared to the elastic forces, structural-oscillation periods can be equal to the wind-force period.

Low or medium-height, rectangular-cross-section buildings and flat plates of height approximately equal to width set normal to a mean turbulent flow exhibit a nearly random response. Instantaneous overturning moments for a rectangular building modeled in the turbulent boundary layer of an urban surrounding (Atlantic-Richfield Towers in Los Angeles) were measured by a strain-gage balance [205]. Peak base-moment fluctuations were found to be ±37 percent of the mean base moment. Measurements of the fluctuating drag force on a square flat plate mounted in a wind tunnel normal to a uniform turbulent flow have been made by Bearman [206]. These measurements shown in Fig. 37 reveal the strong effect of turbulence scale L_x relative to plate size D upon the drag force. As L_x increases relative to D the large scale "gusts" produce a positive pressure fluctuation highly correlated over the upstream plate surface, and a large negative base-pressure fluctuation; therefore, the drag-force fluctuations increase. The fluctuating forces on a bluff body in a turbulent boundary layer are related to the turbulence characteristics in a much more complex manner than Bearman [206] found for the flat plate in a uniform stream—extensive research will be required to establish details for the corresponding aerodynamic admittance functions. Research on this problem is essential for a rational determination of gust-effect factors. These factors appear in a variety of forms in building codes now in use throughout the world.

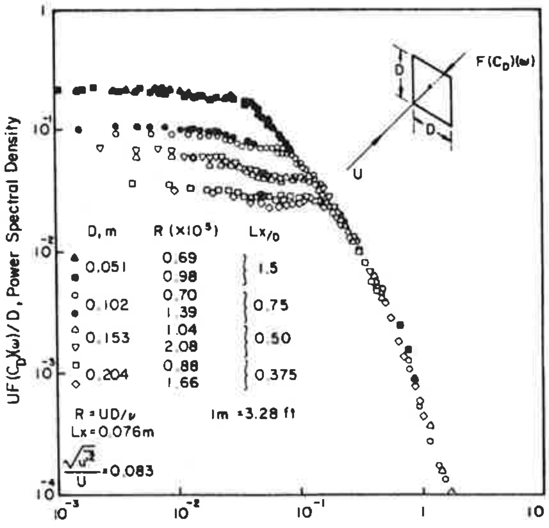

Fig. 37 Power spectral density of unsteady drag on a square flat plate in turbulent flow—Bearman [205]

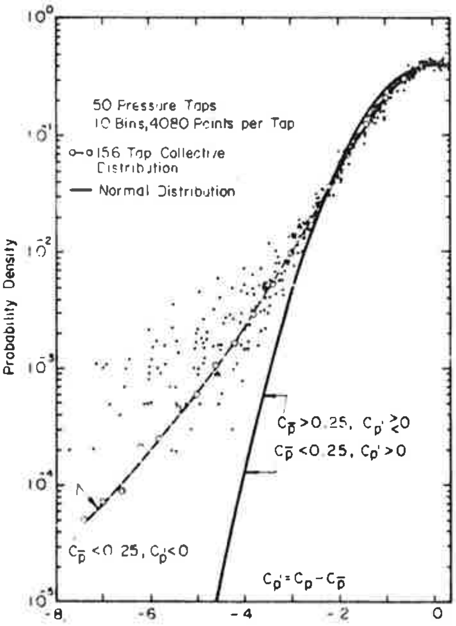

Fig. 36 Probability density distribution for pressure fluctuations on surface of a tall building model in a wind-tunnel boundary layer [81]

Two primary aerodynamic phenomena which develop periodic forces on structures are vortex shedding and galloping. Excitation of tall smoke stacks, tall buildings and bridges by these aerodynamic phenomena has been investigated extensively in wind tunnels by Scruton [195]. Modeling of dynamic effects produced by wind loading introduces requirements for similarity in addition to those for wind. Whitbread [66] has discussed the requirements for elastic similarity in some detail. For tall buildings in which only the fundamental mode of motion is simulated, a commonly used approximation, the additional dimensionless parameters for which equality is required in the scale model and prototype may be summarized as follows:

(*a*) Frequency ratio $\frac{(f_s)_x}{(f_s)_y} = \frac{\text{natural frequency about x-axis}}{\text{natural frequency about y-axis}}$

(*b*) Logarithmic decrement: $\delta_s = \frac{\text{energy dissipation/cycle}}{\text{total energy of oscillation}}$

(*c*) Density ratio: $\frac{\rho_s}{\rho_a} = \frac{\text{average mass density of structure}}{\text{mass density of air}}$

(*d*) Reduced velocity: $\frac{U}{f_s W} = \frac{\text{mean velocity of wind}}{\text{reference oscillation velocity}}$

A common procedure is to mount the model on a gimbals fixed to an inertial platform placed beneath the wind-tunnel floor. An arrangement similar to that used by Whitbread and Scruton [207] is sketched in Fig. 38. Two pairs of mutually perpendicular springs attached to a rod rigidly fixed to the structural shell and passing below the gimbals provides the elastic forces which can be designed to provide the desired natural frequencies. Strain gages attached to the spring mounts can be used to give a voltage output proportional to sway amplitude. Adjustable magnetic damping is provided conveniently by attaching to the support rod a metal plate which passes between the poles of an electromagnet. Variation of current through the magnet permits control of δ_s through a wide range of values.

Typical laboratory data obtained by a system such as shown in Fig. 38 is given by Fig. 39. This set of data clearly reveals strong interdependence between wind characteristics and dynamic response of a tall structure. For the uniform flow (a mean-wind distribution not occurring in nature but grossly approximating wind approaching an isolated structure surrounded by very smooth flat terrain) lateral motion is excited by vortex shedding. In this case the unsteady air motion around the prism is well correlated over the entire building to produce large lateral unsteady forces. When the vortex shedding frequency is near the natural frequency of the building, resonance occurs and large amplitudes result. For the shear flow (a flow closely simulating natural winds for the setting shown in Fig. 33) galloping excitation occurs rather than vortex excitation since vortex shedding does not develop as organized motion over the building. The analytical studies of Novak and Tanaka [77] indicate that the primary effect of turbulence and flow disturbances created by adjacent buildings and the building itself may be to initiate the

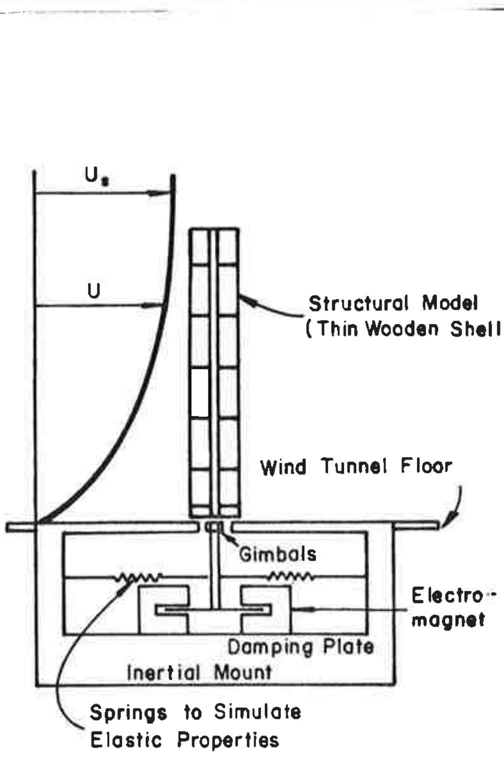

Fig. 38 Typical primary-mode aeroelastic model of a tall building or structure

oscillatory building motion through lateral gust loading. Once the lateral velocity of oscillation has been initiated, a lateral or "lift" force (negative aerodynamic damping) develops through action of the mean wind relative to the building [74]. Since the "lift" forces increase in magnitude with increasing mean relative wind speed, the negative aerodynamic damping will eventually exceed the mechanical damping. Oscillation amplitudes will then continue to increase with wind speed, as shown in Fig. 39—an alarming fact of life! Motion control for galloping excitation is achieved through an increase in mechanical damping, as indicated by the effect of increasing the logarithmic decrement δ_s in Fig. 39.

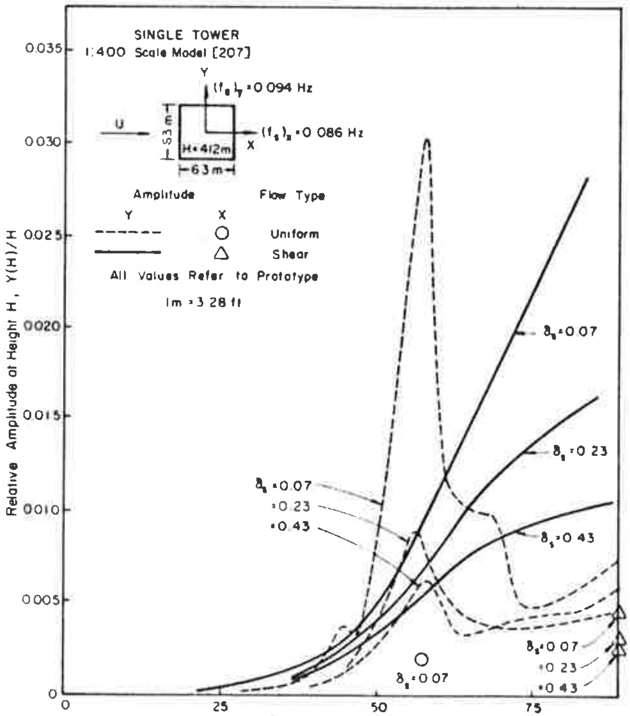

Fig. 39 Dynamic response of a tall building in uniform and boundary-layer flows for a range of structural damping [207]

If tall buildings are to serve their main purpose of providing a place for occupants to live or work in comfort, the accelerations of building motion must be controlled within reasonable perception limits. Dependence of perception thresholds for horizontal acceleration upon period of motion, position of the subject, and information available to the subject are presented by Chen and Robertson [208]. Much research will be required to determine the effects of turbulence, building shape and the proximity of other buildings before dynamic response of a tall building or structure can be determined without recourse to measurements on aeroelastic models in simulated atmospheric winds [209].

Vortex-excited oscillations of circular stacks have been controlled in an effective and practical manner by addition of devices to reduce organized vortex shedding over the entire stack. Three-start helical strakes [67] added to the upper one-third of a stack are shown by the data of Fig. 40 to eliminate vortex excitation. However, the straked cylinder has a drag coefficient two or three times the smooth-cylinder value (for Reynolds numbers in the range of 10^6 to 10^7). This results in larger deflections for the protected stack than for the smooth stack during *strong winds*, as indicated in Fig. 40; however, these are only about 15 percent of the maximum amplitude for the smooth stack. A porous shroud over the upper one-third of a stack and concentric with it also provides good reduction of vortex excitation, as well as a drag coefficient about half that for the straked stack [210].

Stall-type flutter results from the change of moment on a structure due to wind pressures when flow alternately separates and re-

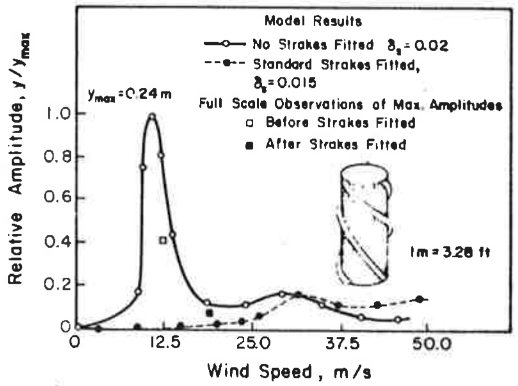

Fig. 40 Oscillation amplitudes for a tapered circular smoke stack with and without helical strakes—Scruton [67]

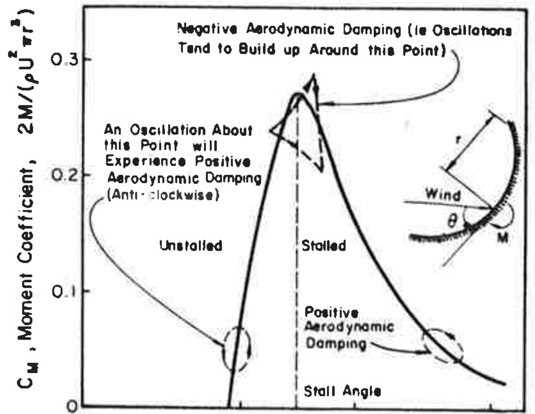

Fig. 41 Stall-type flutter of a reflector bowl [211, 212]

attaches. Structures composed of curved surfaces which do not have strong restraint from rotation are particularly subject to flutter of the stall type. The microwave reflector bowl has an aerodynamic-moment variation with angle-of-attack by the wind as shown in Fig. 41 [211, 212]. A large angular oscillation about the angle of initial stall will occur for this structure unless adequate damping is available.

Suspension bridges exhibit flutter behavior of the classical type. Upon reviewing full-scale measurements of motion on the Golden Gate Bridge, Tanaka and Davenport [72] found that the wind-induced motion at subcritical wind speeds is in the first symmetric vertical mode, which is followed by the first asymmetric mode as the wind speed increases. A disturbing finding was that traditional section models used for wind-tunnel studies of aerodynamic instability do not reproduce the full-scale motions; however, a taut-strip model was found to have this capability [72]. The taut-strip model represents the entire bridge deck by mounting deck sections of scaled geometry and inertia on a parallel pair of tensioned piano wires. To date most of the aerodynamic coefficients for bridge sections of different geometry have been determined by measurements in wind tunnels, using a uniform flow with low turbulence intensities [71]. Because of the strong effect of large-scale turbulence of high intensity upon separation, reattachment and vortex shedding, it is imperative that aerodynamic coefficients be measured in flows which simulate natural atmospheric turbulence.

Summary of Research Needs. Essentially all *mean wind pressure coefficients* for buildings and structures used in practice have been determined by measurements on small-scale models placed in some kind of wind-tunnel flow. Systematic experimental and analytical studies of the following nature should be made in wind-tunnel, boundary-layer flows which accurately simulate the atmospheric boundary layer:

(*a*) Determine mean pressure coefficients for a variety of building shapes subjected to a series of different exposures (different surrounding surface roughness), and

(*b*) Establish the effect of surface roughness, turbulence scale and intensity, and Reynolds number on pressure distributions for circular cylinders and other curved surfaces.

Research to determine mean pressure coefficients for buildings subjected to tornado-like flows is urgently needed.

Instantaneous local wind pressures on building surfaces result in large forces which have caused a substantial number of glass lights to be broken in recent years. Research is urgently needed in the following areas to help overcome this problem:

(*a*) Determine extreme value statistics for pressure fluctuations in regions of separated flow, reattachment and vortex formation,

(*b*) Determine the effect of turbulence scale and intensity in the approaching wind on pressure fluctuations and separation-bubble geometry,

(*c*) Establish similarity requirements for boundary layers which form over rough exterior building surfaces, and

(*d*) Confirm the relationship between time scales for pressure fluctuations on a full-scale building and a small-scale model placed in a simulated atmospheric boundary layer.

Unsteady forces and moments result from the *instantaneous summation of wind pressures* over the entire surface of a building or structure. These, in turn, cause flow-induced vibrations of a nature which depends upon dynamic and geometrical properties of the structure, mechanical damping, and properties of the wind. Systematic experimental studies reinforced by analytical efforts are needed in the following areas:

(*a*) Develop a statistical description for flow-induced motions of stiff buildings for a variety of building shapes and well defined flow characteristics, and determine appropriate forms for the gust-effect factors,

(*b*) Establish the flow conditions (turbulence scales, turbulence intensities, and mean velocity profiles) for a tall, flexible building of a given shape which will cause vortex-excited oscillations and those which will cause galloping,

(*c*) Develop architectural details for tall buildings to modify local flow behavior in an attempt to reduce vortex-induced forces and negative aerodynamic damping, and

(*d*) Determine the aerodynamic coefficients for bridge sections in flows which simulate natural wind conditions.

Measurements of wind pressures and dynamic response of full-scale buildings are essential for confirmation of data obtained from small-scale models. Those investigations must be coordinated closely with laboratory investigations on a small-scale model of the same building, and the measurement of atmospheric variables upwind of the full-scale structure.

7 Definition and Control of Winds

Fluid-mechanical applications to wind-engineering problems related to advection and dispersion of air pollutants are focused primarily on maintaining air-pollutant concentrations within prescribed limits. On the other hand, application of fluid mechanics in the area of wind forces is primarily for the purpose of developing safe, functional, maintenance-free, and comfortable buildings and structures. Other areas of wind engineering require use of fluid mechanics to define the characteristics of wind fields in complex settings, and in many instances to control or modify the local winds. Several of these areas are described briefly in the following paragraphs.

Definition of Wind Fields. Wind data available for wind-engineering purposes are very often confined to data obtained by one Weather Service station—usually located at an airport or on some building within a city. Particularly in areas of nonuniform topography and well built-up urban centers, local winds are greatly different in character than the recorded winds. Davenport [65], by making wind-speed measurements over a small-scale topographic model of the area surrounding Toronto in his boundary-layer wind tunnel, was able to construct probability density distributions for local mean winds within the city from records of wind measurements at the airport. In a like manner, mean winds over the Yerba Buena Center, San Francisco, were correlated by Cermak, Chaudhry, Hansen, and Garrison [164] with Weather Service wind data measured on top of the downtown Federal Office Building.

Small-scale wind-tunnel models of tall buildings and surrounding city geometry designed for wind-pressure investigations may be used to measure wind speeds and turbulence intensities near the street level at the base of tall buildings [201]. Concern for the safety and comfort of pedestrians subjected to strong street-level winds induced by tall structures has stimulated efforts to specify acceptable wind speeds within cities. Penwarden [213] concludes that mean wind speeds of 5 m/s (16 ft/s) represent the threshold of discomfort, 10 m/s (33 ft/s) are unpleasant, and 20 m/s (66 ft/s) and greater are dangerous. Melbourne and Joubert [214] suggest that occurrence of a gust exceeding 23 m/s (75 ft/s) once a year, or 15 m/s (50 ft/s) for one percent of the total time would be unacceptable. Much more study on human response to winds of different turbulence intensities and scales, temperature, humidity, and particulate concentration is needed before objective wind standards for human comfort can be set.

Wind fields over and around proposed elevated STOL-ports must be defined to determine if pilots can safely take off and land their aircraft. The three-dimensional mean-velocity and turbulence field can be determined by measurements over a small-scale model of the planned STOL-port in a meteorological wind tunnel [215]. These data can then be programmed into a flight simulator for pilot training.

Site selection for wind-power installations requires detailed information on local wind characteristics. The local effects of topography, trees and buildings, and atmospheric stability are very complex and are difficult to specify in detail [216]. Wind-engineering data adequate for determining the adequacy of a site for wind-power generation, as well as wind forces on the generator tower, can be obtained most readily through physical modeling of the atmospheric flow over the site. As pointed out by Hewson [217] many opportunities exist for application of wind engineering in this area.

Control of Winds. Wind control is one of the most exciting areas of wind engineering, but perhaps one of the least well developed. To data, most wind-control efforts have been focused on local protection from strong winds through construction of wind breaks [218]. Protection of crops [219], ship-loading docks [220], and research balloons [221] has been achieved effectively by wind breaks and screens. The porous wind break is found to be much more efficient as a wind-energy dissipator than a solid wind break.

Melbourne and Joubert [214] and Wise [179] suggest that selective spacing of low and tall buildings may reduce wind speeds at the base of tall buildings. However, the use of architectural modifications such as projecting canopies [214] and plantings of trees and bushes [164] appear to be the most positive approach to flow control.

Modifications of topography offer opportunities for wind control on a rather large scale. Model studies on flow over Candlestick Park, San Francisco, by Cermak, Malhotra, and Plate [190] revealed that excavation of a cut through the hill immediately upwind, Bayview Hill, would stabilize flow over the ball park.

Wind control by selective grouping of buildings, topographic modification, and selective site development to utilize natural sheltering of existing topographic features requires further research and evaluation. Measures taken to shelter urban sites against wind stress usually increase the probability for excessive air-pollution levels; therefore, the two wind-engineering problems must be considered simultaneously.

Summary of Research Needs. Experimental research to *define local wind characteristics* in a systematic manner is needed to support wind-engineering related to human comfort, transportation and development of new energy sources. Investigations to achieve the following should be undertaken:

(*a*) Develop a statistical description of winds induced at street level by tall buildings,
(*b*) Describe the flow characteristics over the top of structures to be used for heliports, STOL ports, or recreation areas, and
(*c*) Determine the effects of local topography, trees and buildings, and atmospheric stability on wind characteristics at potential wind-power-generation sites.

Control of winds to improve the comfort of pedestrians, reduce wind stress on crops, or protect various outdoor activities may be accomplished by a variety of measures. The most natural control measures which should be studied for wind-reduction efficiency are the following:

(*a*) Wind screens, trees and shrubs and architectural features,
(*b*) Selective grouping of buildings, and
(*c*) Local modifications of topographic features.

8 Conclusion

Fluid mechanics is the basic substance of wind engineering. Winds in the lower atmosphere are best described by reference to fluid motion in turbulent boundary layers and vortices. The wind effects of interest in wind engineering are intimately related to transport of mass, momentum and heat by turbulent fluid motion. However, the fluid mechanics of wind engineering greatly exceeds the complexity of classical fluid mechanics because of complex boundary and initial conditions. The intractability of most wind-engineering problems has caused the fluid-mechanics laboratory to become a catalyst which has combined meteorological and fluid-mechanical knowledge for an attack on these problems.

Motivations similar to those which prompted John R. Freeman [222] to advocate hydraulic laboratories for the study of river problems have stimulated the development of wind tunnels and water channels for wind-engineering investigations. Especially designed meteorological wind tunnels have been developed to simulate essential characteristics of boundary-layer winds for extremely complex boundary conditions. These simulated natural winds permit investigation of wind effects on small-scale models and provide indispensible data for wind-engineering purposes. Development of a comparable capability for simulation of winds and wind effects associated with tornadoes is an urgent need.

Future refinement and extension of current physical modeling capabilities must be complimented by full-scale measurements of wind characteristics and wind effects to confirm validity of the laboratory results. The full-scale investigations should be coordinated carefully with comparable measurements on small scale models. Vigorous analytical investigations of various wind effects must parallel the full-scale and small-scale studies. This effort will provide a framework for correlation of wind-effect data and, hopefully, lead to a good understanding of the physical processes involved.

Continued progress in wind engineering will depend in large measure upon progress in several areas of basic fluid mechanics. If wind engineering is to advance beyond an almost total dependency on laboratory investigations for wind-effect information, much more must be learned about three-dimensional turbulent boundary layers with and without thermal stratification, turbulent separation in unsteady flow, turbulent shear flow over bluff bodies, and interacting turbulent flows of different turbulence characteristics. However, since these are formidable frontiers of turbulent fluid motion, the fluid-mechanics laboratory and the atmosphere itself will continue to be the chief sources of wind-engineering information for the foreseeable future.

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References

1 Freeman, J. R. (ed.), *Hydraulic Laboratory Practice*, ASME, New York, 1929, 868 pp.

2 *Disaster Preparedness*, Report to the Congress, Office of Emergency Preparedness, U. S. Government Printing Office, 3 Vols., Jan. 1972.

3 Sanders, F., "Toward Defining Human Needs: How Does the Atmosphere Hurt Us?" *Bulletin of the American Meteorological Society*, Vol. 52, 1971, pp. 446–449.

4 Cermak, J. E., "Laboratory Simulation of the Atmospheric Boundary Layer," *AIAA Journal*, Vol. 9, No. 9, Sept., 1971, pp. 1746–1754.

5 Cermak, J. E., "Fluid-mechanics Applications to Problems of Wind Forces on Structures and Air Pollution," *Development in Mechanics*, Vol. 7, (Proc. 13th Midwestern Mechanics Conference), University of Pittsburgh, Pittsburgh, Pa., Aug. 1973, pp. 37–53.

6 Tokaty, G. A., *A History and Philosophy of Fluidmechanics*, G. T. Foulis and Co. Ltd., Henly-on-Thames, Oxfordshire, 1971, 241 pp.

7 Richter, J. P., *The Literary Works of Leonardo da Vinci*, Oxford University Press, London, 1939.

8 Galilei, Galileo, *Two New Sciences*, Translation by H. Crew and A. de Salvio, Northwestern University, Evanston, Illinois, 1939, 300 pp.

9 Newton, Sir Isaac, *Sir Isaac Newton's Mathematical Principles of Natural Philosophy*, Revised translation by Florian Cajori, 2 Vols., Greenwood Press, New York, 680 pp.

10 Truesdell, C., "Notes on the History of the General Equations of Hydrodynamics," *American Mathematical Monthly*, Vol. LX, No. 7, 1953, pp. 445–458.

11 Smeaton, J., "An Experimental Investigation Concerning the Natural Powers of Water and Wind," *Phil. Trans. Roy. Soc. of London*, Vol. 51, 1759–1760, pp. 100–174.

12 Bixby, W. H., "Wind Pressures in Engineering Construction," *Engineering News*, Vol. 33, 1895, pp. 174–184.

13 Duchemin, N. V., "Recherches Experimentales sur les Lois de la Resistance des Fluides," *Memorial de l'Artillerie*, Vol. 5, 1842, pp. 65.

14 Reynolds, O., "An Experimental Investigation of the Circumstances Which Determine Whether the Motion of Water Shall Be Direct or Sinuous and of the Law of Resistance in Parallel Channels," *Trans. Roy. Soc. of London*, Vol. A 174, 1883, pp. 935–982.

15 Irminger, I., "Experiments on Wind Pressure," *Proc. Inst. of Civil Engrs.*, Vol. 118, 1893–1894, pp. 468–472.

16 Prandtl, L., "Über Flüssigkeitsgewegung bei sehr kleiner Reibung," *Proc. 3rd Intern. Math. Congr.*, Heidelberg, 1904 (Engl. Trans. NACA TM 452, 1928).

17 Taylor, Sir G. I., "Diffusion by Continuous Movements," *Proc. London Math. Soc.*, Vol. 20, 1920, p. 196.

18 Taylor, Sir G. I., "The Statistical Theory of Turbulence," Parts I-IV, *Proc. Roy. Soc. of London*, Vol. A 151, 1945, p. 421.

19 Kármán, T. von., "Mechanische Ähnlichkeit und Turbulenz," *Nachr. Ges. Wiss. Göttingen*, Math-Phys. Kl, 1930, pp. 58–76.

20 Kolmogorov, A. N., "The Local Structure of Turbulence in Incompressible Viscous Fluid for Very Large Reynolds Numbers," *Doklady AN SSSR*, Vol. 30, No. 4, 1941, pp. 299–303.

21 Richardson, L. F., "The Supply of Energy from and to Atmospheric Eddies," *Proc. Roy. Soc. of London*, Vol. 97, 1920, p. 354.

22 Bjerkness, V., Bjerkness, J., Solberg, H. and Bergeron, T., *Physikalische Hydrodynamik*, Berlin, 1933.

23 Lettau, H. H., *Atmosphärische Turbulenz*, Akademische Verlagsgesellschaft, Leipzig, 1939, 283 pp.

24 Brunt, D., *Physical and Dynamical Meteorology*, Cambridge University Press, 1947.

25 Prandtl, L., "Meteorologische Anwendung der Strömungslehre," *Beiträge zur Physik der Freien Atmosphäre* (Bjerkness-Festschrift), Vol. 19, 1932, p. 188.

26 Prandtl, L. and Reichardt, H., "Einfluss von Wärmeschichtung auf de Eigenschaften einer turbulenten Strömung," *Deutsche Forschung*, No. 21, Berlin, 1934, pp. 110–121.

27 Pagon, W. W., "Aerodynamics and the Civil Engineer," *Engineering News-Record*, Vol. 112, 1934, pp. 348–353; Vol. 113, 1934, pp. 41–43; Vol. 113, 1934, pp. 456–458; Vol. 113, 1934, pp. 814–818; Vol. 114, 1935, pp. 582–586; Vol. 114, 1935, pp. 665–668; Vol. 114, 1935, pp. 742–745; Vol. 115, 1935, pp. 601–609.

28 Stanton, T. E., "Report on Measurement of the Pressure of the Wind on Structures," *Proc. Inst. of Civil Engr.*, Vol. 219, 1924–1925, pp. 125–158.

29 Bailey, A., "Wind Pressures on Buildings," Institution of Civil Engineers Selected Engineering Paper No. 189, 1933.

30 Bailey, A., and Vincent, N. D. G., "Wind-Pressures on Buildings Including Effects of Adjacent Buildings," Jl. Institution of Civil Engineers, Vol. 20, No. 8, Oct. 1943, pp. 243–275.

31 Scruton, C., "Experimental Investigation of the Aerodynamic Stability of Suspension Bridges," National Physical Laboratory, Aero. Rept. No. 165, 1948.

32 Abe, M., "Mountain Clouds, Their Forms and Connected Air Currents," *Bull. Cent. Meteor. Obs.*, Vol. 7, No. 3, Tokyo, 1929.

33 Field, J. H. and Warden, R., "A Survey of the Air Currents in the Bay of Gibraltar in 1929–1930," Air Ministry, Meteor. Office Geophys. Mem., No. 59.

34 Sherlock, R. H. and Stalker, E. A., "A Study of Flow Phenomena in the Wake of Smokestacks," Engr. Res. Bull. No. 29, University of Michigan, 1941, 49 pp.

35 Albertson, M. L., "Analysis of Evaporation as a Boundary Layer," PhD dissertation, State University of Iowa, Iowa City, Iowa, 1948, 50 pp.

36 Kármán, T. von, "Aerodynamics and the Art of the Engineer," *Mémoires de la Société des Ingenieurs Civils de France*, 1948, pp. 155–178, (Nat. Res. Council of Canada, Tech. Trans. 894, Ottawa, 1960, 29 pp.).

37 Sutton, O. G., *Micrometeorology*, McGraw-Hill, 1953, 333, pp.

38 Monin, A. S., and Obukhov, A M., "Basic Laws of Turbulent Mixing in the Ground Layer of the Atmosphere," *Trudy Geofizs. Inst. An SSSR*, 2, No. 24 (15 p.), 1954, pp. 163–187, (see Monin, A. S. and Yaglom, A. M., "Statistical Fluid Mechanics: Mechanics of Turbulence: Vol. 1, MIT Press, Cambridge, Massachusetts, 1971, pp. 425–442).

39 Panofsky, H. A., "The Atmospheric Boundary Layer Below 150 Meters," *Annual Review of Fluid Mechanics*, Vol. 6, 1974, pp. 147–177.

40 Van der Hoven, I., "Power Spectrum of Horizontal Wind Speed in the Frequency Range From 0.0007 to 900 Cycles Per Hour," *Journal of Meteorology*, Vol. 14, 1957, pp. 160–164.

41 Davenport, A. G., "The Spectrum of Horizontal Gustiness Near the Ground in High Winds," *Quart. Journal Roy. Met. Soc.*, Vol. 89, 1961, p. 194.

42 Hanna, S. R., "Characteristics of Winds and Turbulence in the Planetary Boundary Layer," ESSA Research Laboratories, Air Resources Laboratory Tech. Memo. ERLTM-ARL8, Oak Ridge, Tenn., 1969, 67 pp.

43 Lettau, H. H., "Theoretical Wind Spirals in the Boundary Layer of a Barotropic Atmosphere," *Beitr. Phys. Atmos.*, Vol. 35, 1962, pp. 195–212.

44 Carrier, G. G., Hammond, A. L., and George, O. D., "A Model of the Mature Hurricane," *Journal of Fluid Mechanics*, Vol. 23, 1966, pp. 25–42.

45 Kuo, H. L., "On the Dynamics of Convective Atmospheric Vortices," *Journal of the Atmospheric Sciences*, Vol. 23, 1966, pp. 25–42.

46 Kuo, H. L., "Note on the Similarity Solutions of the Vortex Equations in an Unstable Atmosphere," *Journal of the Atmospheric Sciences*, Vol. 24, 1967, pp. 95–97.

47 Fultz, D., "Experimental Analogies to Atmospheric Motions," *Compendium of Meteorology*, American Meteorological Society, Boston, 1951, pp. 1235–1248.

48 Fultz, D., "Non-Dimensional Equations and Modeling Criteria for the Atmosphere," *Journal of Meteorology*, Vol. 8, 1951, pp. 262–267.

49 Rouse, H., "Model Techniques in Meteorological Research," *Compendium of Meteorology*, American Meteorological Society, Boston, 1951, pp. 1249–1254.

50 Cermak, J. E., Sandborn, V. A., Plate, E. J., Binder, G. H., Chuang, H., Meroney, R. N., and Ito, S., "Simulation of Atmospheric Motion by Wind-Tunnel Flows," Fluid Dynamics and Diffusion Laboratory, Technical Report No. CER66JEC-VAS-EJP-GJB-HC-RNM-SI17, Colorado State University, Fort Collins, Colo., May 1966, 101 pp.

51 Cermak, J. E., and Arya, S. P. S., "Problems of Atmospheric Shear Flows and Their Laboratory Simulation," *Boundary-Layer Meteorology*, Vol. 1, 1970, pp. 40–60.

52 Hidy, G. M., "On Atmospheric Simulation: A Colloquium," National Center for Atmospheric Research, Technical Note 22, 1966, 270 pp.

53 Strom, G. H., "Wind Tunnel Techniques Used to Study Influence of Building Configuration on Stack Gas Dispersal," *American Industrial Hygiene Association Quarterly*, Vol. 13, 1952, p. 76.

54 Cermak, J. E., "Wind Tunnel for the Study of Turbulence in the Atmospheric Surface Layer," Fluid Dynamics and Diffusion Laboratory, Technical Report CER58-JEC42, Colorado State University, Fort Collins, Colorado, 1958, 31 pp.

55 Plate, E. J., and Cermak, J. E., "Micro-meteorological Wind Tunnel Facility," Fluid Dynamics and Diffusion Laboratory, Technical Report CER63EJP-JEC9, Colorado State University, Fort Collins, Colo., 1963, 65 pp.

56 Clark, J. W., "Laboratory Investigations of Atmospheric Shear Flows Using an Open Channel," *Proceedings of AGARD Conference on Aerodynamics of Atmospheric Shear Flows*, AGARD Conf. Proc. 48, 1969, pp. 15.1–15.15.

57 Plate, E. J., "A Research Facility with Concurrent Air and Water Flows," *La Houille Blanche*, No. 6, 1965, pp. 595–598.

58 Coantic, M., Bonmarin, P., Pouchain, B., and Favre, A., "Etude d'une Soufflerie pour Recherches sur les Echanges d'Energie Atmosphere-Oceans," *Proceedings of AGARD Conference on Aerodynamics of Atmospheric Shear Flows*, AGARD Conf. Proc. No. 48, 1969, pp. 17.1–17.14.

59 Teunissen, H. W., "Simulation of the Planetary Boundary Layer in a Multiple-Jet Wind Tunnel," Institute for Aerospace Studies, Rept. 182, University of Toronto, Toronto, Canada, 1972, 162 pp.

60 Counihan, J., "An Improved Method of Simulating an Atmospheric Boundary Layer in a Wind Tunnel," *Atmospheric Environment*, Vol. 3, 1969, pp. 197–214.

61 Cermak, J. E., and Koloseus, H. J., "Lake Hefner Model Studies of Wind Structure and Evaporation," Fluid Dynamics and Diffusion Laboratory, Tech. Repts. CER54-JEC20 and CER54-JEC22, (AD 1054930), Colorado State University, Fort Collins, Colorado, 1953–1954, 275 pp.

62 Jensen, M., "The Model-Law for Phenomena in Natural Wind," *Ingeniøren*, Vol. 2, No. 4, 1958, pp. 121–128.

63 Pasquill, F., *Atmospheric Diffusion*, S. von Nostrand Co., 1962, 297 pp.

64 Davenport, A. G., "Applications of Statistical Concepts to the Wind Loading of Structures," *Proceedings Institution of Civil Engineers*, Vol. 19, 1961, pp. 449–472.

65 Davenport, A. G., "On the Statistical Prediction of Structural Performance in the Wind Environment," Paper presented at ASCE National Structural Meeting, Baltimore, Md., Preprint 1420, 1971, 30 pp.

66 Whitbread, R. E., "Model Simulation of Wind Effects on Structures," *Proceedings of Conference on Wind Effects on Buildings and Structures*, National Physical Laboratory, Teddington, Great Britain, 1965, pp. 283–306.

67 Scruton, C., "On the Wind-Excited Oscillations of Stacks, Towers and Masts," *Proceedings of Conference on Wind Effects on Buildings and Structures*, Teddington, Great Britain, 1965, pp. 798–836.

68 Farquharson, F. B., "Aerodynamic Stability of Suspension Bridges with Special Reference to the Tocoma Narrows Bridge," University of Washington Experiment Station, Engineering Bulletin 116, Parts I-V, 1949–1954.

69 Scruton, C., "An Experimental Investigation of the Aerodynamic Stability of Suspension Bridges with Special Reference to the Proposed Severn Bridge," *Proceedings Institution of Civil Engineers*, Vol. 1, Part 1, 1952, pp. 189–192.

70 Hirai, A., Okauchi, I., and Miyata, J., "On the Behaviour of Suspension Bridges under Wind Action," *Proceedings Symposium on Suspension Bridges*, Lisbon, Portugal, 1966.

71 Scanlan, R. H., "An Examination of Aerodynamic Response Theories and Model Testing Relative to Suspension Bridges," *Proceedings of the Third International Conference on Wind Effects on Buildings and Structures*, Tokyo, Japan, 1971, pp. 941–951.

72 Tanaka, H., and Davenport, A. G., "The Aerodynamic Stability of the Golden Gate Bridge: Comparison of the Full-Scale Motion with a Taut Strip Wind Tunnel Model," Paper presented at Symposium on Full-Scale Measurements of Wind Effect on Tall Buildings and Other Structures, The University of Western Ontario, London, Ontario, 1974, 24 pp.

73 Roshko, A., "On the Drag and Shedding Frequency of Two-Dimensional Bluff Bodies," NACA TN3169, Washington, 1954, 29 pp.

74 Den Hartog, J. P., *Mechanical Vibrations*, McGraw-Hill, New York, 1956, pp. 299–305.

75 Parkinson, G. V., "Aeroelastic Galloping in One Degree of Freedom," *Proceedings of Conference on Wind Effects on Buildings and Structures*, National Physical Laboratory, Teddington, Great Britain, 1963, pp. 582–609.

76 Novak, M., "Galloping Oscillation of Prismatic Structures," *Journal of the Engineering Mechanics Division*, ASCE, Vol. 98, No. EM1, Feb. 1972, pp. 27–46.

77 Novak, M. and Tanaka, H., "Effect of Turbulence on Galloping Instability," *Journal of the Engineering Mechanics Division*, ASCE, Vol. 100, No. EM1, Feb. 1974, pp. 27–47.

78 Davenport, A. G., "The Action of Wind on Suspension Bridges," *Proceedings Symposium on Suspension Bridges*, Lisbon, Portugal, 1966, pp. 79–107.

79 Cermak, J. E., "Separation-Induced Pressure Fluctuations on Buildings," *Proceedings of Seminar on Wind Loads on Structures*, University of Hawaii, Honolulu, Hawaii, Oct. 1970, pp. 55–70.

80 Sadeh, W. Z., and Cermak, J. E., "Turbulence Effects on Wall Pressure Fluctuations," *Journal of Engineering Mechanics*, ASCE, Vol. 98, No. EM6, 1972, pp. 1365–1379.

81 Peterka, J. A., and Cermak, J. E., "Probability Distributions of Wind Pressure Fluctuations on Buildings," Paper presented at ASCE Specialty Conference on Probabilistic Methods in Engineering, Stanford University, Palo Alto, California, June, 1974, 15 pp.

82 Sadeh, W. Z., Sutera, S. P., and Maeder, P. F., "An Investigation of Vorticity Amplification in the Flow Approaching a Two-Dimensional Stagnation Point," *Z. Angew. Math. Phys.*, Vol. 21, 1970, pp. 699–742.

83 Hunt, J. C. R., "A Theory of Turbulent Flow Around Two-Dimensional Bluff Bodies," *Journal of Fluid Mechanics*, Vol. 61, Part 4, 1973, pp. 625–706.

84 Colin, P. E., and D'Havé, R., "Exécution in Tunnel Aérodynamique d'Essais sur Marquettes de Bâtiments en Rapport avec les Mesures Faites sur Constructions Réelles," *Proceedings of Conference on Buildings and Structures*, National Physical Laboratory, Teddington, Great Britain, 1963, pp. 255–282.

85 Newberry, C. W., Eaton, K. J., and Mayne J. R., "Wind Pressure and Strain Measurements at the Post Office Tower," Building Research Establishment, Current Paper 30/73, Garston, Watford, 1973, 35 pp.

86 Dalgliesh, W. A., "Cladding Pressures on Commerce Court Tower, Toronto," Paper presented at Symposium on Full-Scale Measurements of Wind Effects on Tall Buildings and Other Structures, The University of Western Ontario, London, Ontario, 1974, 13 pp.

87 Miyoshi, S., Ida, M. and Miura, T., "Wind Pressure Coefficients on Exterior Wall Elements of a Tall Building," *Proceedings of the Third International Conference on Wind Effects on Buildings and Structures*, Tokyo, Japan, 1971, pp. 273–284.

88 Chiu, A. N. L., and Taoka, G. T., "Tower Response to Actual and Simulated Wind Forces," *Journal of the Structural Division*, ASCE, Vol. 99, No. ST9, Sept. 1973, pp. 1911–1929.

89 Schuëller, G. I., and Wittmann, F. H., "Reliability Considerations Based on Measurements of Wind Effects Taken at the Munich Television Tower," Paper presented at the Symposium on Full-Scale Measurements of Wind Effects on Tall Buildings and Other Structures, University of Western Ontario, London, Ontario, 1974, 22 pp.

90 Roshko, A. (ed.), "Wind Loads on Structures," Summary Report on a Conference held at the California Institute of Technology (sponsored by the National Science Foundation), Pasadena, California, Dec. 1970, 137 pp.

91 Scruton, C., "The Use of Wind Tunnels in Industrial Aerodynamics Research," National Physical Laboratory, Great Britain, NPL/Aero/411, 1960, 53 pp.

92 Rogers, E. W. E., and Whitbread, R. E., "Industrial Aerodynamics: A Survey of Research in the United Kingdom," National Physical Laboratory, Great Britain, NPL Aero Report 1200, July 1966, 111 pp.

93 Lumley, J. L., and Panofsky, H. A., *The Structure of Atmospheric Turbulence*, Interscience Publishers, New York, 1964, 239 pp.

94 Smagorinsky, J., "General Circulation Experiments with the Primitive Equations," *Monthly Weather Review*, Vol. 91, No. 3, 1963, pp. 99–164.

95 Thom, H. C. S., "New Distributions of Extreme Winds in the United States," Paper presented at ASCE Environmental Engineering Conference, Dallas, Texas, Conference Preprint 431, 1967, 22 pp.

96 Kessler, E., "Survey of Boundary Layer Winds with Special Reference to Extreme Values," Paper 74-586, 7th Plasma and Fluid Dynamics Conference, American Institute of Aeronautics and Astronautics, Palo Alto, California, June 1974, 19 pp.

97 Hanna, S. R., "Characteristics of Winds and Turbulence in the Planetary Boundary Layer," ESSA Research Laboratories,

Air Resources Laboratory, Oak Ridge, Tennessee, Technical Memorandum ERLTM-ARL 8, 1969, 61 pp.

98 Blackadar, A. K., "The Vertical Distribution of Wind and Turbulent Exchange in a Neutral Atmosphere," *Journal of Geophysical Research*, Vol. 67, 1962, pp. 3095–3102.

99 Blackadar, A. K., "A Simplified Two-Layer Model of the Baroclinic Neutral Atmospheric Boundary Layer," The Mineral Industries Experiment Station, The Pennsylvania State University, Final Report Contract No. AF (604)-6641, 1965, pp. 49–62.

100 Hoxit, L. R., "Variability of Planetary Boundary Layer Winds," Department of Atmospheric Science, Colorado State University, Paper No. 199, 1973, 157 pp.

101 Deardorff, J. W., "Numerical Investigation of Neutral and Unstable Planetary Boundary Layers," *Journal of the Atmospheric Sciences*, Vol. 29, 1972, pp. 91–115.

102 Donaldson, C. du P., "Calculation of Turbulent Shear Flows for Atmospheric and Vortex Motions," *AIAA Journal*, Vol. 10, No. 1, 1972, pp. 4–12.

103 Lumley, J. L., and Khajeh-Nouri, B., "Computational Modeling of Turbulent Transport," *Advances in Geophysics*, Vol. 18, 1973.

104 Archibald, E. D., "Some Results of Observations with Kite-Wire Suspended Anemometers up to 1300 Feet Above the Ground in 1883–1885," *Nature*, Vol. 33, 1886, pp. 593–595.

105 Klebanoff, P. S., and Diehl, Z. W., "Some Features of Artificially Thickened Fully Developed Turbulent Boundary Layers With Zero Pressure Gradient," National Advisory Committee for Aeronautics, Technical Note 2475, Washington, 1951, 55 pp.

106 Davenport, A. G., "A Rationale for Determination of Design Wind Velocities," *Proceedings ASCE, Journal of the Structural Division*, Vol. 86, 1960, pp. 39–66.

107 Davenport, A. G., "The Relationship of Wind Structure to Wind Laoding," *Proceedings of Conference on Buildings and Structures*, National Physical Laboratory, Great Britain, 1963, pp. 54–83.

108 Monin, A. S., "Turbulence in the Atmospheric Boundary Layer," *The Physics of Fluids Supplement*, Vol. 10, Part II of Two Parts, No. 9, *Proceedings of International Symposium on Boundary Layers and Turbulence with Geophysical Applications*, Kyoto, Japan, Sept. 1966, 1967, pp. 531–537.

109 Cermak, J. E., "Determination of Wind Loading on Structural Models in Wind-Tunnel Simulated Winds," *Proceedings of Design Symposium on Wind Effects on High-Rise Buildings*, Northwestern University, Evanston, Ill., 1970, pp. 61–88.

110 Businger, J. A., "Turbulent Transfer in the Atmospheric Surface Layer," *Workshop on Micrometeorology* (Duane Haugen, ed.), American Meteorological Society, Boston, 1973, pp. 67–100.

111 Kaimel, J. C., "Turbulence Spectra, Length Scales and Structure Parameters in the Stable Surface Layer," *Boundary-Layer Meteorology*, Vol. 4, Apr. 1973, pp. 289–309.

112 Fichtl, G. H., "Longitudinal and Lateral Spectra in the Atmospheric Boundary Layer at the Kennedy Space Center," *Journal of Applied Meteorology*, Vol. 9, No. 1, 1970, pp. 51–63.

113 Kaimal, J. C., Wyngaard, J. C., Izumi, T., and Coté, O. R., "Spectral Characteristics of Surface-Layer Turbulence," *Quarterly Journal of the Royal Meteorological Society*, Vol. 98, 1972, pp. 563–589.

114 Graham, H. E., and Hudson, G. N., "Surface Winds Near the Center of Hurricanes (and other Cyclones)," National Hurricane Research Project, Report No. 39, Washington, 1960, 200 pp.

115 Elsberry, R. L., Pearson, N. A. S., and Corgnati, L. B. Jr., "A Quasi-Empirical Model of the Hurricane Boundary Layer," *Journal of Geophysical Research*, Vol. 79, No. 21, 1974, pp. 3033–3040.

116 Golden, J. H., "Life Cycle of Florida Keys' Waterspouts," National Severe Storms Laboratory, NOAA Technical Memo. ERL NSSL-70, June 1974, 147 pp.

117 Penner, S. S., "Elementary Considerations of the Fluid Mechanics of Tornadoes and Hurricanes," *Astronautica Acta*, Vol. 17, 1972, pp. 351–362.

118 Morton, B. R., "Geophysical Vortices," *Progress in Aeronautical Sciences*, Vol. 7, 1966, pp. 145–194.

119 Hoecker, W. H., Jr., "Wind Speed and Air Flow Patterns in the Dallas Tornado of April 2, 1957," *Monthly Weather Review*, Vol. 88, No. 5, May 1960, pp. 167–180.

120 Hoecker, W. H., Jr., "Three-Dimensional Pressure Pattern of the Dallas Tornado and Some Resultant Implications," *Monthly Weather Review*, Vol. 89, No. 12, 1961, pp. 533–542.

121 Fujita, T. T., "A Proposed Characterization of Tornadoes and Hurricanes by Area and Intensity," Satellite and Mesometeorology Research Projects Paper 91, Department of Geophysical Sciences, University of Chicago, Chicago, Illinois, 1971, 42 pp.

122 Fujita, T. T., and Pearson, A. D., "Results of FFP Classification of 1971 and 1972 Tornadoes," Preprints of Eighth American Meteorological Society Conference on Severe Local Storms, Denver, Colorado, October, 1973, pp. 142–145.

123 Dergarabedian, P., and Fendell, F., "Estimation of Maximum Wind Speeds in Tornadoes," *Tellus*, Vol. 22, 1970, pp. 511–516.

124 Markee, E. H., Jr., Beckerley, J. G., and Sanders, K. E., "Technical Basis for Interim Regional Tornado Criteria," U. S. Atomic Energy Commission, WASH-1300 (UC-11), Superintendent of Documents, U. S. Government Printing Office, Washington, May 1974, 23 pp.

125 Kuo, H. L., "Axisymmetric Flows in the Boundary Layer of a Maintained Vortex," *Journal of the Atmospheric Sciences*, Vol. 28, No. 1, Jan. 1971, pp. 20–41.

126 Nicholson, F. H., and Johnson, D. R., "A New Vortex Model Based on a Zero Laplacian of Vorticity," Technical Report under NSF Grant GA-30978X, Department of Meteorology, University of Wisconsin, Madison, Wis., Mar. 1973, 64 pp.

127 Bonner, W. D., "Statistical and Kinematical Properties of the Low-Level Jet Stream," Satellite and Mesometeorology Research Project, Paper 38, Department of Geophysical Sciences, University of Chicago, Chicago, Ill. 1965, 54 pp.

128 Brinkman, W. A. R., "A Climatological Study of Strong Downslope Winds in the Boulder Area," National Center for Atmospheric Research, Cooperative Thesis No. 27, Boulder, Colo., 1973, 228 pp.

129 Meroney, R. N., "Buoyancy Effects on a Turbulent Shear Flow," Preprints of American Meteorological Society Symposium on Atmospheric Diffusion and Air Pollution, Santa Barbara, Calif. Aug. 1974, pp. 25–30.

130 Ruark, A. E., "Inspectional Analysis: A Method Which Supplements Dimensional Analysis," *Journal Elisha Mitchell Science Society*, Vol. 51, 1935, pp. 127–133.

131 Zoric, D. and Sandborn, V. A., "Similarity of Large Reynolds Number Boundary Layers," *Boundary-Layer Meteorology*, Vol. 2, No. 3, Mar. 1972, pp. 326–333.

132 Chuang, H., and Cermak, J. E., "Similarity of Thermally Stratified Shear Flows in the Laboratory and Atmosphere," *The Physics of Fluids Supplement*, Vol. 10, Part II, No. 9, *Proceedings of an International Symposium on Boundary Layers and Turbulence With Geophysical Applications*, Kyoto, Japan, Sept. 1966, 1967, pp. S255–S258.

133 Barad, M. L., (ed.), "Project Prairie Grass—A Field Program in Diffusion," Geophysical Research Paper 59, Geophysical Research Directorate, Bedford, Mass., 1952.

134 Pond, S., Stewart, R. W., and Burling, R.-W., "Turbulence Spectra in Wind Over Waves," *Journal of the Atmospheric Sciences*, Vol. 20, 1963, pp. 319–324.

135 Cermak, J. E., and Chuang, H., "Vertical-Velocity Fluctuations in Thermally Stratified Shear Flows," *Proceedings of International Colloquium on Atmospheric Turbulence and Radio Wave Propagation*, Publishing House 'Nauka,' Moscow, U.S.S.R., 1965, pp. 93–104.

136 Schlichting, H., *Boundary Layer Theory*, McGraw-Hill, Inc., 1960, 647 pp.

137 Chaudhry, F. H., and Cermak, J. E., "Wind-Tunnel Modeling of Flow and Diffusion Over an Urban Complex," Fluid Dynamics and Diffusion Laboratory Technical Report CER70-71FHC-JEC24 (Project THEMIS Report No. 17), Colorado State University, Fort Collins, Colo., 1971, 70 pp.

138 Nee, V. W., Dietrick, C., Betchov, R., and Szewczyk, A. A., "The Simulation of the Atmospheric Surface Layer with Volumetric Flow Control," *Proceedings of Nineteenth Annual Technical Meeting*, Institute of Environmental Science, Anaheim, Calif., 1973, pp. 483–487.

139 Morkovin, M. V., Nagib, H. M., and Yung, J. T., "On Modeling of Atmospheric Surface Layers by the Counter-Jet Technique—Preliminary Results," Tech. Rept. AFSOR-TR-73-0592, Illinois Institute of Technology, Chicago, Ill., 1972.

140 Counihan, J., "Simulation of an Adiabatic Urban Boundary Layer in a Wind Tunnel," *Atmospheric Environment*, Vol. 7, 1973, pp. 673–689.

141 Standen, N. M., "A Spire Array for Generating Thick Turbulent Shear Layers for Natural Wind Simulation in Wind Tunnels," Tech. Rept. LTR-LA-94, National Aeronautical Establishment, Ottawa, Canada, 1972.

142 Sundaram, T. R., Ludwig, G. R., and Skinner, G. T., "Modeling of the Turbulence Structure of the Atmospheric Surface Layer," *AIAA Journal*, Vol. 10, 1972, pp. 743–750.

143 Peterka, J. A., and Cermak, J. E., "Simulation of Atmospheric Flows in Short Wind Tunnel Test Sections," Fluid Dynamics and Diffusion Laboratory, Tech. Rept. CER73-74JAP-JEC32, Colorado State University, Fort Collins, Colo.,

1974, 52 pp.

144 Caldwell, D. R., and Van Atta, C. W., "Some Measurements of Instabilities in Ekman Boundary Layers," *Proceedings of AGARD Conference on Aerodynamics of Atmospheric Shear Flows*, AGARD Conf. Proc. No. 42, 1969, pp. 22.1–22.13.

145 Caldwell, D. R., and Van Atta, C. W., "Ekman Boundary Layer Instabilities," *Journal of Fluid Mechanics*, Vol. 44, Part 1, October, 1970, pp. 79–95.

146 Ekman, V. W., "On jordrotationens inverkan på vindströmmar i hafvet," *Nytt Mag. For Naturv.*, Vol. 40, 1902, pp. 37–63.

147 Faller, A. J., "An Experimental Study of the Instability of the Laminar Ekman Boundary Layer," *Journal of Fluid Mechanics*, Vol. 15, 1966, pp. 560–576.

148 Chang, C. C., "Tornado Effects on Buildings and Structures with Laboratory Simulation," *Proceedings of Third International Conference on Wind Effects on Buildings and Structures*, Tokyo, Japan, 1971, pp. 231–240.

149 Ward, N. B., "The Exploration of Certain Features of Tornado Dynamics Using a Laboratory Model," *Journal of the Atmospheric Sciences*, Vol. 29, No. 6, 1972, pp. 1194–1204.

150 Hsu, C. T., "Laboratory Modeling of the Tornado Suction Mechanism," Preprints of Eighth American Meteorological Society Conference on Severe Local Storms, Denver, Colorado, Oct. 1973, pp. 199–202.

151 Cermak, J. E., "Lagrangian Similarity Hypothesis Applied to Diffusion in Turbulent Shear Flow," *Journal of Fluid Mechanics*, Vol. 15, No. 1, 1963, pp. 49–64.

152 Chaudhry, F. H., and Meroney, R. N., "Similarity Theory of Diffusion and the Observed Vertical Spread in the Diabatic Surface Layer," *Boundary-Layer Meteorology*, Vol. 3, No. 4, 1973, pp. 405–415.

153 Briggs, G. A., "Plume Rise," AEC Critical Review Series, TID-25075, Clearinghouse for Federal Scientific and Technical Information, Springfield, Virginia, 1969, 81 pp.

154 Fay, J. A., "Buoyant Plumes and Wakes," *Annual Review of Fluid Mechanics*, Vol. 5, 1973, pp. 151–160.

155 Csanady, G. T., *Turbulent Diffusion in the Environment*, D. Reidel Publ. Co., 1973, 248 pp.

156 Hoult, D. P., and Weil, J. C., "Turbulent Plume in a Laminar Cross Flow," *Atmospheric Environment*, Vol. 6, 1972, pp. 513–531.

157 Hoot, T. G., and Meroney, R. N., "The Behavior of Negatively Buoyant Stack Gases," Preprint Paper No. 74–120, 67th Annual Meeting of the Air Pollution Control Association, Denver, Colo., June 1974, 20 pp.

158 Smith, M. (ed.), "Recommended Guide for the Prediction of the Dispersion of Airborne Effluents," American Society of Mechanical Engineers, New York, N. Y., 1968, 85 pp.

159 Slade, D. H. (ed.), "Meteorology and Atomic Energy," U. S. Atomic Energy Commission, TIC-24190, Clearinghouse for Federal Scientific and Technical Information, Springfield, Va., 1968, 445 pp.

160 Turner, D. B., "Workbook of Atmospheric Dispersion Estimates," Public Health Service Publication No. 999-AP-26, National Air Pollution Control Administration, Cincinnati, Ohio, 1969, 84 pp.

161 Donaldson, C. du P., "Atmospheric Turbulence and the Dispersal of Atmospheric Pollutants," Aeronautical Research Associates of Princeton, Inc., Tech. Rept. Contract No. 68-02-0014, U. S. Environmental Protection Agency, Washington, D. C., 1973, 197 pp.

162 Cermak, J. E., and Nayak, S. K., "Wind-Tunnel Model Study of Downwash from Stacks of a Fossil Fuel Power Plant," Fluid Dynamics and Diffusion Laboratory, Technical Report CER72-73JEC-SKN28, Colorado State University, Fort Collins, Colo., 1973, 58 pp.

163 Leutheusser, H. J., and Motycka, J., "Redesign of Refinery Stacks by Wind Tunnel Tests to Meet Changes in Crude Oil Quality," Preprint Paper No. 74-163, 67th Annual Meeting of the Air Pollution Control Association, Denver, Colo., June 1974, 21 pp.

164 Cermak, J. E., Chaudhry, F. H., Hansen, A. C., and Garrison, J. A., "Wind and Air-Pollution Control Study of Yerba Buena Center, San Francisco," Fluid Dynamics and Diffusion Laboratory, Technical Report CER71-72JEC-FHC-ACH-JAG15, Colorado State University, Fort Collins, Colorado, 1972, 73 pp.

165 Chaudhry, F. H., and Cermak, J. E., "Study of Wind Pressures and Air Quality Around Children's Hospital, National Medical Center, Washington, D. C.," Fluid Dynamics and Diffusion Laboratory, Technical Report CER70-71FHC-JEC55, Colorado State University, Fort Collins, Colo., 1971, 72 pp.

166 Meroney, R. N., Cermak, J. E., and Chaudhry, F. H., "Wind Tunnel Model Study of Shoreham Nuclear Power Station Unit I, Long Island, New York," Fluid Dynamics and Diffusion Laboratory, Technical Report CER68-69RNM-JEC-FHC1, Colorado State University, Fort Collins, Colo., 1968, 74 pp.

167 Mousson, B., Bessemoulin, P. J., Hausard, M., and Boulay, J. C., "Atmospheric Pollution Study and Prevision Over the New Town of Saint-Quentin-En-Yvelines in France," Preprint Paper No. 74-158, 67th Annual Meeting of the Air Pollution Control Association, Denver, Colo., June 1974, 16 pp.

168 Strom, G. H., and Halitsky, J., "Important Considerations in the Use of the Wind Tunnel for Pollution Studies of Power Plants," Paper No. 54-SA-41, American Society of Mechanical Engineers Semi-Annual Meeting, Pittsburgh, Pennsylvania, June 1954, 25 pp.

169 Lord, G. R., and Leutheusser, H. J., "Wind-Tunnel Modelling of Stack Gas Discharge," *Man and His Environment*, Vol. 1, Pergamon Press, Inc., 1970, pp. 115–125.

170 Meroney, R. N., Cermak, J. E., Garrison, J. A., Yang, B. T., and Nayak, S. K., "Wind-Tunnel Study of Stack Gas Dispersal at the Avon Lake Power Plant," Fluid Dynamics and Diffusion Laboratory, Technical Report CER73-74RNM-JEC-BTY-SKN35, Colorado State University, Fort Collins, Colo., Apr. 1974, 239 pp.

171 Isyumov, N., Jandali, T., and Davenport, A. G., "Model Studies and the Prediction of Full Scale Levels of Stack Gas Concentrations," Preprint Paper No. 74-162, 67th Annual Meeting of the Air Pollution Control Association, Denver, Colo., June 1974, 33 pp.

172 Chaudhry, F. H., and Meroney, R. N., "Turbulent Diffusion in a Stably Stratified Shear Layer," Fluid Dynamics and Diffusion Laboratory, Technical Report CER69-70FHC-RNM-12, Colorado State University, Fort Collins, Colo., Sept. 1969, 204 pp.

173 Strom, G. H., and Gerdel, R. W., "Scale Simulation of a Blowing Snow Environment," *Proceedings of the Institute of Environmental Science*, Vol. 53, 1961, pp. 53–63.

174 Iverson, J. D., Greeley, R., Pollack, J. B., and White, B. R., "Simulation of Martian Eolian Phenomena in the Atmospheric Wind Tunnel," Engineering Research Institute, Technical Paper ERI-73083, Iowa State University, Ames, Iowa, 1973, 25 pp.

175 Halitsky, J., "Validation of Scaling Procedures for Wind Tunnel Model Testing of Diffusion Near Buildings," Geophysical Sciences Laboratory, Report No. TR-69-8, New York University, New York, 1969, 195 pp.

176 Sherlock, R. H., and Lesher, E. J., "Design of Chimneys to Control Downwash of Gases," TRANS. ASME, Jan. 1955, pp. 1–9.

177 Ruscheweyh, H., "Flue Gas Concentrations in the Effect Range of a Power Plant, as Investigated in the Wind Tunnel with the Aid of a Model," *Staub-Reinhalt-Luft*, Vol. 32, No. 5, May 1972, pp. 11–20.

178 Sakagami, J., and Kato, M., "Effects of Complicated Topography on Diffusion—Wind Tunnel Experiments," Natural Science Report, Vol. 19, No. 1, Ochanomizu University, Tokyo, Japan, 1968, 21 pp.

179 Wise, A. F. E., "Effects Due to Groups of Buildings," *Phil. Trans. of the Royal Society of London*, Series A, Vol. 269, No. 1199, 1971, pp. 469–485.

180 Mair, W. A., and Maull, D. J., "Bluff Bodies and Vortex Shedding—A Report on Euromech 17," *Journal of Fluid Mechanics*, Vol. 45, Part 2, 1971, pp. 209–224.

181 Halitsky, J., "Gas Diffusion Near Buildings," *Transactions of American Society of Heating, Refrigeration and Air-Conditioning Engineers*, Vol. 69, 1963, pp. 476–477.

182 Lighthill, M. J., and Silverleaf, A. (eds.), "A Discussion on Architectural Aerodynamics," *Phil. Trans. of the Royal Society of London*, Series A, Vol. 269, No. 1199, 1971, pp. 321–554.

183 "Urban Climates," *Proceedings of Symposium on Urban Climates and Building Climatology*, Tech. Note No. 108, World Meteorological Organization, Geneva, Switzerland, 1968, 389 pp.

184 "Building Climatology," *Proceedings of Symposium on Urban Climates and Building Climatology*, Tech. Note No. 109, World Meteorological Organization, Geneva, Switzerland, 1968, 260 pp.

185 Cermak, J. E., Lombardi, D. J., and Thompson, R. S., "Applications of Physical Modeling to the Investigation of Air-Pollution Problems in Urban Areas," Preprint Paper No. 74-160, 67th Annual Meeting of the Air Pollution Control Association, Denver, Colo., June 1974, 26 pp.

186 Hoydish, W. G., Griffiths, R. A., and Ogawa, Y., "A Scale Model Study of the Dispersion of Pollution in Street Canyons," Preprint Paper No. 74-157, 67th Annual Meeting of the Air Pollution Control Association, Denver, Colo., June 1974, 24 pp.

187 Lavery, T. F., Egan, B. A., and Iwanchuk, R. M., "The Numerical Simulation of the Advection and Diffusion of a Plume

Under Aerodynamic Downwash Conditions," Reprint Paper No. 74-215, 67th Annual Meeting of the Air Pollution Control Association, Denver, Colo., June 1974, 16 pp.

188 Hunt, J. C. R., and Mulhern, P. J., "Turbulent Dispersion from Sources Near Two-Dimensional Obstacles," *Journal of Fluid Mechanics*, Vol. 61, Part 2, 1973, pp. 245–274.

189 Briggs, B. A., "Airflow Around a Model of the Rock of Gibraltar," Meteorological Office, Scientific Paper No. 18, Her Majesty's Stationery Office, London, 1963, 20 pp.

190 Cermak, J. E., Malhotra, R. C., and Plate, E. J., "Investigation of the Candlestick Park Wind Problem, Vol. II: Wind-Tunnel Model Study," Fluid Dynamics and Diffusion Laboratory, Technical Report No. CER63JEC-RCM-EJP27, Colorado State University, Fort Collins, Colo., 1963, 77 pp.

191 Cermak, J. E., and Peterka, J. A., "Simulation of Wind Field Over Point Arguello, California by Wind-Tunnel Flow Over a Topographc Model," Fluid Dynamics and Diffusion Laboratory, Technical Report No. CER65JEC-JAP64, Colorado State University, Fort Collins, Colo., 1966, 75 pp.

192 Orgill, M. M., and Cermak, J. E., "Atmospheric Flow and Diffusion Over Mountainous Terrain," Paper No. 72-648, 5th Fluid and Plasma Dynamics Conference, American Institute for Aeronautics and Astronautics, Boston, Mass., June 1972, 11 pp.

193 Lin, J. T., Liu, H. T., and Pao, Y. H., Laboratory Simulation of Plume Dispersion in a Stably Stratified Flow Over a Complex Terrain," Preprint Paper No. 74-161, 67th Annual Meeting of the Air Pollution Control Association, Denver, Colo., June 1974, 20 pp.

194 Buettner, K. J. K., and Thyer, N., "Valley Winds in the Mount Rainier Area," *Arch. Met. Biokl.*, Ser. B, Vol. 14, No. 2, 1965, pp. 125–147.

195 Scruton, C., "Aerodynamics of Structures," *Proceedings of International Research Seminar on Wind Effects on Buildings and Structures*, Ottawa, Canada, Sept. 1967, pp. 115–161.

196 Peterka, J. A., and Cermak, J. E., "Wind-Engineering Study of the Federal Reserve Bank Building, Richmond," Fluid Dynamics and Diffusion Laboratory, Technical Report CER73-74JAP-JEC8, Colorado State University, Fort Collins, Colo., 1973, 157 pp.

197 Fage, A., and Warsap, J. H., "The Effects of Turbulence and Surface Roughness on the Drag of a Circular Cylinder," British Aeronautical Research Council, Report R & M 1283, 1929, 14 pp.

198 Armitt, J., "The Effect of Surface Roughness and Free Stream Turbulence on the Flow Around a Model Cooling Tower at Critical Reynolds Numbers," *Proceedings of Symposium on Wind Effects on Buildings and Structures*, Loughborough University of Technology, Loughborough, England, Apr. 1968, pp.6.1–6.13.

199 Vickery, B. J., "Fluctuating Lift and Drag on a Long Cylinder of Square Cross Section in a Smooth and in a Turbulent Stream," *Journal of Fluid Mechanics*, Vol. 25, Part 3, 1966, pp. 481–494.

200 Ostrowski, J. S., Marshall, R. D., and Cermak, J. E., "Vortex Formation and Pressure Fluctuations on Buildings," *Proceedings of International Seminar on Wind Effects on Buildings and Structures*, Ottawa, Canada, Sept. 1967, pp. 459–484.

201 Marshall, R. D., and Cermak, J. E., "Wind Studies of Bank of America World Headquarters Building—Part II, Wind Tunnel Study," Fluid Dynamics and Diffusion Laboratory, Technical Report CER66-67RDM-JEC19, Colorado State University, Fort Collins, Colo., 1966, 66 pp.

202 Cermak, J. E., and Sadeh, W. Z., "Pressure Fluctuations on Buildings," *Proceedings of the Third International Conference on Wind Effects on Buildings and Structures*, Tokyo, Japan, Sept. 1971, pp. 189–198.

203 Roshko, A., "On the Aerodynamic Drag of Cylinders at High Reynolds Numbers," *Proceedings of Seminar on Wind Loads on Structures*, University of Hawaii, Honolulu, Hawaii, Oct. 1970, pp. 87–98.

204 Standen, N. M., Dalgliesh, W. A., and Templin, R. J., "A Wind Tunnel and Full-Scale Study of Turbulent Wind Pressures on a Tall Building," *Proceedings of the Third International Conference on Wind Effects on Buildings and Structures*, Tokyo, Japan, Sept. 1971, pp. 199–209.

205 Cermak, J. E., Sadeh, W. Z., and Hsi, G., "Fluctuating Moments on Tall Buildings Produced by Wind Loading," *Proceedings of Technical Meeting Concerning Wind Loads on Buildings and Structures*, National Bureau or Standards, 1969, (SD Catalog No. C 13.29/2:30, Superintendent of Documents, U. S. Government Printing Office, Washington, D. C.,) pp. 45–59.

206 Bearman, D. W., "Fluctuating Forces On Bluff Bodies in Turbulent Flow," Proceedings of Conference on the Aerodynamics of Atmospheric Shear Flows, AGARD Conference Proceedings No. 48, Munich, Germany, 1969, pp. 24.1–24.13.

207 Whitbread, R. E., and Scruton, C., "An Investigation of the Aerodynamic Stability of a Model of the Proposed Tower Blocks for the World Trade Cneter, New York," National Physical Laboratory, Aero. Rept. 1156, 40 pp.

208 Chen, P. W., and Robertson, L. E., "Human Perception of Thresholds of Horizontal Motion," *Proceedings of the American Society of Civil Engineers, Journal of the Structural Division*, Vol. 98, No. ST8, August, 1972, pp. 1681–1695.

209 Cermak, J. E., "Wind Effects on Tall Buildings—Areas for Research," *Proceedings of ASCE-IABSE International Conference on Planning and Design of Tall Buildings*, Vol. 1b Lehigh University, August, 1972, pp. 435–440.

210 Walshe, D. E., "Wind-Tunnel Investigations of the Dynamic Behaviour of Some Tall Stacks and Gas-Turbine Exhaust Towers," *Proceedings of Symposium on Wind Effects on Buildings and Structures*, Loughborough University of Technology, Loughborough, England, Apr. 1968, pp. 17.1–17.28.

211 Scruton, C., "Some Consideration of Wind Effects on Large Structures," in *Structures Technology for Large Radio and Radar Telescope Systems* (J. W. Mar and H. Liebowitz, eds.), MIT Press, 1969.

212 Wootton, L. R., and Scruton, C., "Aerodynamic Stability," *Proceedings of Seminar on the Modern Design of Wind Sensitive Structures*, The Institution of Civil Engineers, London, England, June 1970, Construction Research and Information Association, 6 Storey's Gate, London, pp. 65–81.

213 Penwarden, A. D., "Acceptable Wind Speeds in Towns," *Building Science*, Vol. 8, No. 3, Sept. 1973, pp. 259–267.

214 Melbourne, W. H., and Joubert, P. N., "Problems of Wind Flow at the Base of Tall Buildings," *Proceedings of Third International Conference on Wind Effects on Buildings and Structures*, Tokyo, Japan, Sept. 1971, pp. 105–114.

215 Peterka, J. A., and Cermak, J. E., "A Wind Model for an Elevated STOL-Port Configuration," NASA CR-2450, National Aeronautics and Space Adminsitration, Washington, D. C., July 1974, 39 pp.

216 Davidson, B. (chairman), Gerbier, N., Papagianakis, S. D., and Rijkoort, P. J., "Sites for Wind-Power Installations," World Meteorological Oranization, Tech. Note No. 63, Geneva, Switzerland, 1964, 37 pp.

217 Hewson, E. W., "Wind Power Research at Oregon State University," *Proceedings of NSF/NASA Worksiop on Wind Energy Conversion Systems*, NSF/RA/W-73-006, Washington, D. C., June 1973, pp. 53–61.

218 Eimern, J. von (chairman), Karschon, R., Razumova, L. A., and Robertson, G. W., "Windbreaks and Shelterbelts," World Meteorological Organization, Tech. Note No. 59, Geneva, Switzerland, 1964, 188 pp.

219 Miller, D. R., Rosenberg, N. J., and Bagley, W. T., "Soybean Water Use in the Shelter of a Slat-Fence Windbreak," *Agricultural Meteorology*, Vol. 11, No. 3, June 1973, pp. 405–418.

220 Valensi, J., and Flinois, A., "Établissement D'un mur Pare-Vent Perforé pour les Navires a Qui," Association Technique Maritime et Aéronautique, Session 1955, 21 pp.

221 Meroney, R. N., and Plate, E. J., "Wind-Tunnel Investigation of Shapes for Balloon Shelters," *Journal of Applied Meteorology*, Vol. 11, No. 5, Aug. 1972, pp. 849–857.

222 Freeman, J. R., "The Need for a National Hydraulic Laboratory for the Solution of River Problems," *Transactions of the American Society of Civil Engineers*, Vol. LXXXVII, 1924, pp. 1033–1097.