ference, Univ. of Wisconsin, Madison, Wis., April 16–18, 1965, Wiley, New York, 1967, pp. 141–146.

[6] Timoshenko, S. and Woinowsky-Krieger, S., *Theory of Plates and Shells*, 2nd ed., McGraw-Hill, New York, 1959.

[7] Watson, G. N., *A Treatise on the Theory of Bessel Functions*, 2nd ed., Cambridge University Press, England, 1962, p. 405.

[8] Buchwald, V. T., "A Mixed Boundary-Value Problem in the Elementary Theory of Elastic Plates," *Quarterly Journal of Mechanics and Applied Mathematics*, Vol. 10, 1957, pp. 183–190.

[9] Gladwell, G. M. L., "Some Mixed Boundary Value Problems in Isotropic Thin Plate Theory," *Quarterly Journal of Mechanics and Applied Mathematics*, Vol. 11, 1958, pp. 159–171.

[10] Werner, H. and Peter, J., "Beitrag zur Berechnung von Platten mit teilweiser Randeinspannung und teilweise einspannungsfreier Auflagerung," *Der Stahlbau*, Vol. 35, No. 4, 1966, pp. 97–106.

[11] Gradshteyn, I. S. and Ryzhic, I. M., *Table of Integrals, Series and Products*, 4th ed., Academic Press, New York, 1965, pp. 427, 584.

[12] Dwight, H. B., *Tables of Integrals and Other Mathematical Data*, 4th ed., Macmillan, New York, 1969, pp. 179–186.

[13] Goodier, J. N., "The Influence of Circular and Elliptical Holes on the Transverse Flexure of Elastic Plates," *Philosophical Magazine*, Vol. 22, 1936, pp. 69–80.

[14] Sih, G. C., Paris, P. C., and Erdogan, F., "Crack-Tip, Stress-Intensity Factors for Plane Extension and Plate Bending Problems," *Journal of Applied Mechanics*, Vol. 29, 1962, pp. 306–312.

[15] Yu, Y. Y., "The Influence of a Small Hole or Rigid Inclusion on the Transverse Flexure of Thin Plates," *Proceedings of the Second U.S. National Congress of Applied Mechanics*, 1954, pp. 381–387.

[16] Williams, M. L., "The Bending Stress Distribution at the Base of a Stationary Crack," *Journal of Applied Mechanics*, Vol. 28, 1961, pp. 78–82.

[17] Williams, M. L., "Surface Stress Singularities Resulting from Various Boundary Conditions in Angular Corners of Plates Under Bending," *U.S. National Congress of Applied Mechanics*, Illinois Inst. of Technology, Chicago, Ill., June 1952, pp. 325–329.

[18] Kantorovich, L. V. and Krylov, V. I., *Approximate Methods of Higher Analysis*, Interscience, New York, 1958, pp. 101–102.

[19] Leissa, A. W., Clausen, W. E., Hulbert, L. E., and Hopper, A. T., "A Comparison of Approximate Methods for the Solution of Plate Bending Problems," *AIAA Journal*, Vol. 7, No. 5, May 1969, pp. 920–928.

[20] Stahl, B. and Keer, L. M., "Vibration and Stability of Cracked Rectangular Plates," *International Journal of Solids and Structures*, Vol. 8, 1972, pp. 69–91.

JUNE 1972 AIAA JOURNAL VOL. 10, NO. 6

Modeling of the Turbulence Structure of the Atmospheric Surface Layer

T. R. Sundaram,* G. R. Ludwig,† and G. T. Skinner‡
Cornell Aeronautical Laboratory Inc., Buffalo, N.Y.

Theoretical and experimental concepts relevant to the laboratory simulation of the turbulence characteristics of the atmospheric surface layer are discussed. It is argued that, for proper simulation, the laboratory flow must satisfy the requirements of horizontal homogeneity, aerodynamically rough flow and proper thermal stratification. A discussion is also given of the manner in which the similitude criteria can be used to derive the dimensions of a laboratory facility required for proper modelling. Experiments on the generation of laboratory flows which can be used to simulate neutrally-stable atmospheric surface layers are described. A fairly simple technique, in which the flow near the floor of a wind tunnel is "tripped" by a flat-plate fence spanning the width of the tunnel and then allowed to develop over a rough ground, is shown to provide suitable flows provided that the height of the fence is carefully matched to the aerodynamic roughness of the roughness elements. The turbulence characteristics of the laboratory flows generated using the present technique compare very well with the corresponding characteristics of atmospheric-surface-layer flows.

Introduction

In recent years increasing interest has developed in various environmental problems which are influenced, as well as controlled, by the boundary-layerlike behavior of the atmospheric motions near the Earth's surface. Many of the natural phenomena that are crucial to the support of life on the Earth take place within the planetary boundary layer. This layer is a highly complex entity, and the motions within it are generally turbulent and notoriously difficult to analyze. It is impossible to obtain satisfactory theoretical solutions to certain problems, such as the diffusion of emissions from a low stack on a building in the lee of a large complex of buildings. These problems are influenced not only by the atmospheric turbulence field, but also by the turbulence generated by the buildings themselves. Although actual observations in the atmosphere have yielded some results on such problems, much insight into the relevant phenomena has not been gained since conditions in the atmosphere are essentially uncontrolled and uncontrollable. Thus, laboratory modeling of the turbulence structure of the lower atmosphere in a wind tunnel like facility seems to hold much promise.

The use of wind tunnels to study atmospheric problems has a fairly long history. The early basic studies on turbulent boundary layers in wind tunnels also shed much light on similar problems in the atmosphere. For example, the well-known logarithmic law for the wind profile in a neutrally stable atmosphere was deduced from Nikuradse's experiments on the flow in rough-walled pipes and conduits.[1,2] A number of early attempts were also made to use conventional, aeronautical-type wind tunnels to model

Presented as Paper 71-136 at the AIAA 9th Aerospace Sciences Meeting, New York, January 25–27, 1971; submitted March 24, 1971; revision received February 15, 1972. This paper is based upon research sponsored by the U.S. Atomic Energy Commission Contract AT (30-1)-4038 and by CAL Internal Research (W/A 86-232).

Index category: Atmospheric, Space, and Oceanographic Sciences.

* Principal Aeronautical Engineer; present address Hydronautics Inc., Laurel, Md. Member AIAA.

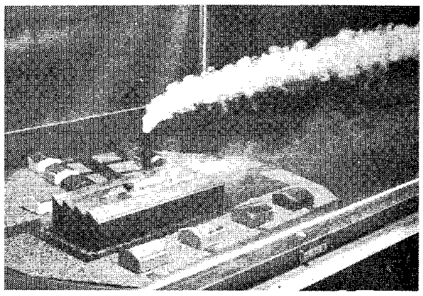
† Principal Aeronautical Engineer. Member AIAA.

‡ Principal Aeronautical Engineer.

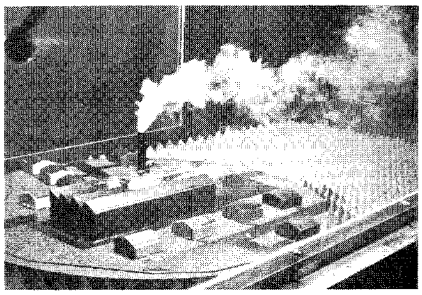
specific problems in the atmosphere such as the flow in the lee of large objects, diffusion from smoke stacks and similar problems.[3-5] Only in recent years has it come to be recognized that the turbulent boundary-layerlike behavior of atmospheric flows near the Earth's surface controls many of the important phenomena taking place in the lower atmosphere.

The importance of proper modeling of the turbulence structure of the atmosphere can be demonstrated quite simply by comparing the behavior of a smoke plume in unsimulated and correctly simulated flow. In Fig. 1a, a (1/600) scale model of a factory chimney (whose top is 150 ft above ground) is placed in a uniform flow. It can be seen from Fig. 1a that the model plume in a uniform flow diffuses slowly, since the dispersion is only due to the self-generated turbulence in the plume. Figure 1b shows the flow past the same model when the turbulence characteristics and the mean shears in the flow approaching the model have been simulated to correspond to those upstream of the real factory. Note that in this case the model plume exhibits the characteristic "looping" of a real plume.

A number of recent studies[6-8] have firmly established the feasibility of simulating, in the laboratory, some important classes of atmospheric problems. Extensive experimental demonstrations of the practicability of simulating a wide variety of atmospheric flows have been given by Strom and Halitsky,[9] Arya and Plate,[10] Cermak and Arya[11] and others.[12-14] Nevertheless, a careful investigation of the experimental and theoretical requirements for simulating the turbulence structure of the lower atmosphere, and a delineation of the general operating requirements of a laboratory facility to generate the proper flows, have not been made. The present paper deals with both aspects. In the next section some of the important characteristics of the atmospheric surface layer that have to be modeled in order to achieve proper simulation are discussed briefly; more complete discussions have been given elsewhere.[15,16] The operating requirements of a laboratory facility to model the characteristics of the turbulence in the atmospheric surface layer are then deduced. Next, experimental studies on the generation of laboratory flows suitable for the simulation of neutrally stable atmospheric flows are discussed, and finally some concluding remarks are given in the last section.



a) UNIFORM FLOW



b) SIMULATED ATMOSPHERIC SURFACE LAYER

Fig. 1 Comparison of smoke plume behavior in incorrectly and correctly simulated flows.

Theoretical Aspects of Atmospheric Simulation

Before proceeding with a discussion of the requirements for similarity between the laboratory boundary layer and the atmospheric surface layer, a few preliminary remarks regarding the differences between the two flows are appropriate. The great disparity in scale between the atmospheric and laboratory boundary layers introduces certain significant differences between the two. As Ellison[17] points out, the regions of greatest accessibility and interest in the atmospheric boundary layer are those closest to the ground. Moreover, the actual thickness of the planetary boundary layer and its dynamic evolution are assumed to be of little importance when seeking a theoretical description of the atmospheric surface layer. For example, surface-layer theories such as the Monin-Obukhov[18] theory assume that certain "external parameters" (such as the friction velocity u_*) are specified close to the ground, and they seek a description of the surface layer entirely in terms of these quantities alone. The fact that these "external parameters" may themselves be dependent upon large-scale synoptic features such as the geostrophic wind and the Coriolis parameter (see Lettau)[19] has no bearing on these theories. On the other hand, when a theoretical description of the entire planetary boundary layer including the Ekman spiral is sought, the geostrophic wind and the Coriolis parameter will appear explicitly in the result (see Ellison,[20] for example).

Clearly, the entire planetary boundary layer (including the Ekman spiral) cannot be modeled by a wind-tunnel boundary layer.§ It is also clear that the geostrophic wind has no correspondence to the freestream velocity outside the wind-tunnel boundary layer. Therefore, the only portion of a laboratory boundary layer that can be used to model the atmosphere is that portion which can be described entirely in terms of conditions specified at the surface alone and does not depend explicitly on the freestream velocity. Correspondingly, the only part of the planetary boundary layer that can be modeled properly in the laboratory is that portion which can be described in terms of conditions at the surface alone and does not depend on the geostrophic wind.¶ This simple, almost obvious, fact seems to have been overlooked by some workers engaged in modeling.

In the literature, there are two basically different approaches that have been used to simulate the turbulence structure of the lower atmosphere. In the first approach, a thick turbulent boundary layer is grown "naturally" over the rough floor of a wind tunnel with a long test section. It is then argued that the turbulence characteristics of this boundary layer can be expected to be similar to those of the atmosphere provided that certain similitude criteria are satisfied by the mean flow.[21] In the second approach,[22-26] various devices, such as shear screens and grids, are used at the entrance to a relatively short test section so as to artificially thicken the turbulent boundary layer. The devices are chosen such that the characteristics at a specified location correspond to those of the atmosphere.

It is clear from the statements made earlier that the entire depth of a laboratory boundary layer, irrespective of whether it was generated "naturally" or "artificially," cannot be considered to be suitable model for the atmosphere. Indeed, extensive measurements made in a "naturally" grown boundary layer[21] have shown that only the lower regions of this boundary layer correspond to the atmosphere. The major disadvantage of "artificially" thickened boundary layers is that conditions in the basic flow vary fairly rapidly with distance from the perturbing devices at the entrance of the test section even when no model is present in the flow. As will be seen below, horizontal homogeneity is one of the key requirements for proper simulation of the surface layer characteristics.

§ Coriolis force cannot be modeled directly in a wind tunnel, and other devices such as the so-called "dish-pan" or rotating tanks are necessary.

¶ The practically important problem of the simulation of wind force on tall buildings is included in this statement and will be discussed in more detail later in this section.

It can be shown[15] that below a height of about 100 m in the atmosphere, the effects of Coriolis forces can be neglected and that over this height the variation of the value of the shear stress is only about 20%. It is this bottom 100 m of the atmosphere (the so-called surface layer) that is most amenable to wind-tunnel simulation, and will be the subject of our discussion in the present paper. Specifically, in the remainder of this section the principal characteristics of the surface layer, which are important from the point of view of simulation, will be discussed. These characteristics are horizontal homogeneity, aerodynamic surface roughness and thermal stratification.

The assumption of horizontal homogeneity is implicit in most surface-layer theories, and the actual thickness of the surface layer or its dynamic evolution (in the horizontal direction) is not explicitly considered in these theories. As Ellison[17] points out, an appropriate mathematical model for the flow in the surface layer is to view it as that in the vicinity of an infinite rough plane (which supports a fluid of great depth), to which a constant shear stress and a constant heat flux are applied. In this model it is assumed that conditions close to the plane reach a steady state which is independent of conditions at great distances away from the plane, in the sense that the flow in the regions close to the plane can be described entirely in terms of the applied shear stress and the heat flux.

Thus the assumption of horizontal homogeneity is a necessary part of surface-layer theories, since only under this assumption can it be asserted that conditions close to the surface can be specified in terms of surface conditions alone. In other words, the "external parameters" approach and the assumption of horizontal homogeneity are closely related. A detailed discussion of the implication of the assumption of horizontal homogeneity and its relation to the similarity theory of Monin and Obukhov,[18] has been given by Calder.[27]

It may be argued that horizontally homogeneous flows seldom occur in practice in the atmosphere, and that therefore it is of questionable value to simulate such flows in the laboratory. However, it should be emphasized that horizontally homogeneous flows serve as an important standard for studying other flows, and the fact that they seldom occur in practice is of little relevance here. Thus when constructing a mathematical model for the atmospheric flow over an obstacle, the proper approach would be to postulate that the flow far ahead of the obstacle is horizontally homogeneous. This condition would then specify the initial vertical distributions of velocity and turbulence statistics in the flow approaching the obstacle, and the perturbations in these due to the obstacle can be calculated. Similarly, the wind-tunnel modeling of the atmospheric flow over an obstacle can be viewed as analogue modeling in which the appropriate initial conditions are satisfied by creating a horizontally homogeneous flow. The flow over the obstacle is then modeled by assuring equivalence between the model and atmospheric flows of certain similitude parameters.

An important exception to the requirement of horizontal homogeneity occurs in the practically important problem of the simulation of wind loads on, and flows over, tall structures located in urban areas. In such problems the major part of the turbulence in the flow is produced locally by the buildings themselves. Specifically, at any given location the characteristics of the turbulence are not influenced by the characteristics of the turbulence considerably upstream of that location. Moreover, in such cases the region dominated by surface influences extends to considerable heights and the flow in the region of interest does not depend explicitly on geostrophic effects. Thus when modeling the above flows it is often sufficient to model the mean-velocity profile alone, provided that the buildings upstream of the location under consideration are modeled for sufficiently long distances. Much pioneering work on the wind effects on tall structures has been carried out by Davenport[22,28] and his co-workers and by Cermak.[29] It should be pointed out that the above remarks do not apply for the case of an isolated tall structure located in the midst of smaller buildings. For this case it is necessary to model properly the characteristics of the turbulence in the flow approaching the tall structure.

A second characteristic of the atmospheric surface layer which is important from the point of view of laboratory simulation is aerodynamic roughness. A flow over a rough surface is said to be fully aerodynamically rough when there is no laminar sublayer close to the surface.[1] That is, in such flows the effects of molecular viscosity are negligible even in regions close to the surface. Fully aerodynamically rough flows occur when the heights of the roughness elements on the surface are greater than the height of the laminar sublayer that would have existed on a smooth surface under identical flow conditions.

The concept of aerodynamic roughness is an important one for atmospheric simulation, since atmospheric flows are almost always fully aerodynamically rough.[2] Thus, for proper similarity, it is necessary to insure that the laboratory flow is aerodynamically rough also. The condition for the existence of fully aerodynamically rough flow is given by $(u_* z_0/\nu) \gtrsim 3$, where u_* is the friction velocity, z_0 is the roughness length of the ground and ν is the kinematic viscosity of air. As will be seen in the next section, the above condition has an important bearing on the operating requirements of an atmospheric simulation facility.

A third important characteristic of the atmospheric surface layer is thermal stratification. When a vertical gradient in the potential temperature exists in the atmosphere, the resulting buoyancy forces influence the structure of the turbulence in a profound manner. The most convenient similitude parameter to characterize the effects of thermal stratification[8] is the parameter B_0, given by

$$B_0 = (gH/u_0^2)\Delta T_0/T_{av} \tag{1}$$

where H is a reference height (which can be taken as the height of the surface layer), u_0 is the velocity at the reference height, ΔT_0 is the difference in temperature between the surface and the reference height, g is the acceleration due to gravity and T_{av} is the average absolute temperature in the region of interest. Thus, an appropriate criterion for laboratory simulation of thermal stratification effects is

$$(gH_t/u_{0_t}^2)(\Delta T_0/T_{av})_t = B_{0_a} \tag{2}$$

where the subscripts t and a refer to the tunnel and atmosphere, respectively. It should be emphasized that in the parameter B_0, the temperature difference ΔT_0 has to be interpreted in terms of the potential temperature difference.

Modeling of the atmospheric surface layer is not, of course, an end in itself. The final objective of modeling the surface layer is the ability to model such processes as diffusion taking place in it. Thus, it is necessary to investigate the similitude criteria not only for the surface layer itself, but also for these processes. The criteria for each of these processes have to be considered individually, and no general discussion will be attempted here. A special case that will be considered here, and will be relevant to later discussions, is the case of modeling of the flow around an object immersed in the atmospheric surface layer. If the height of the structure or object is denoted by h and if the roughness length of the ground upstream of the structure is z_0, then it can be shown[8] that for proper similarity the quantity (h/z_0) should be the same for the model and the prototype. The preceding similitude was first stated by Jensen[30] and has since been used widely in the literature.

The significance of Jensen's criterion for the present context is that one can state the corresponding criterion for modeling the entire depth of the surface layer as

$$H_a/z_{0_a} = H_t/z_{0_t} \tag{3}$$

where H_a is the height of the surface layer, z_{0_a} is the roughness length for a given atmospheric flow, H_t is the height of the laboratory test flow and z_{0_t} is the roughness length of the laboratory flow required to simulate the given atmospheric flow. The importance of Eq. (3) for choosing the design parameters of an atmospheric simulation facility is discussed in the next section.

Operating Requirements for a Laboratory Facility

The similitude criteria that are important for the laboratory simulation of atmospheric-surface-layer flows have been outlined

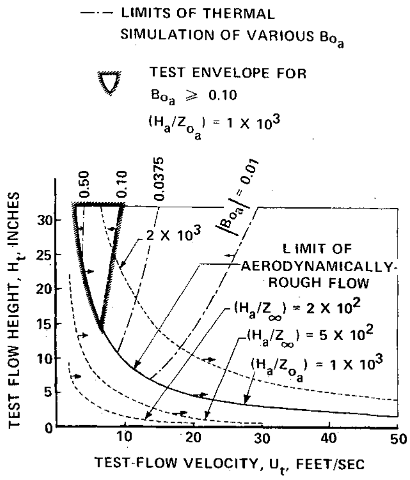


Fig. 2 Limits of laboratory simulation of the atmospheric surface layer.

briefly in the preceding section. The manner in which the above criteria can be used to deduce the operating requirements for an atmospheric simulation facility is described in the present section.

As mentioned before, one of the necessary conditions that must be satisfied by the model flow is that it be fully aerodynamically rough. This condition is satisfied if

$$u_{*_t} z_{0_t}/\nu \gtrsim 3 \tag{4}$$

In neutrally stable, constant-stress layers the velocity u_t at the height H_t is related to the friction velocity through the logarithmic relation[2]

$$u_t = (u_{*_t}/k)\log_e(H_t/z_{0_t}) \tag{5}$$

where k is the von Kármán constant.

Equations (4) and (5) can be combined to yield

$$H_t \gtrsim (3\nu/ku_t)(H_t/z_{0_t})\log_e(H_t/z_{0_t}) \tag{6}$$

Since for proper similitude between atmospheric and model flows Eq. (3) also has to be satisfied, it follows that

$$H_t \geqq (3\nu/ku_t)(H_a/z_{0_a})\log_e(H_a/z_{0_a}) \tag{7}$$

This inequality gives the minimum value of the height of the tunnel test flow to attain fully aerodynamically rough flow for different values of the tunnel velocity, u_t, and the ratio (H_a/z_{0_a}).

The value of the von Kármán constant is about 0.4 and the kinematic viscosity of air at 15°C is about 1.55×10^{-4} ft²/sec. When these values are used in Eq. (6), one obtains the relation

$$H_t \gtrsim (2.67 \times 10^{-3}/u_t)(H_a/z_{0_a})\log_{10}(H_a/z_{0_a}) \tag{8}$$

where H_t is in feet and u_t is in feet per second. In the atmosphere, the values of z_0 vary over rather wide ranges depending on the type of surfaces considered. For fully grown root crops, z_0 is about 10 cm, for downland it is about 1 cm and for the sea in moderate wind it is about 0.1 cm. For flows over forests and urban areas z_0 will be considerably higher than the values just quoted.

If a value of 10 cm is taken as being a typical value of z_{0_a}, the value of (H_a/z_{0_a}) is about one thousand (since H_a is about 100 m). The relation given in Eq. (8) is shown plotted in Fig. 2 for a value of $(H_a/z_{0_a}) = 10^3$. The interpretation of the curve is that fully aerodynamically rough flow can be maintained at all tunnel conditions represented by the region to the right-hand side of the curve. Thus if the maximum available height of the test flow is 15 in., fully aerodynamically rough flow can be maintained only for velocities above 6 fps, while if the available height is 5 in., proper simulation is possibly only beyond a velocity of 20 fps. For purposes of comparison the curves corresponding to values of (H_a/z_{0_a}) of 2000, 500, and 200 are also shown in Fig. 2.

When thermal stratification effects have to be simulated, Eq. (1) provides an additional relation between the tunnel velocity u_t and the height, H_t, of the test flow. Equation (1) can be rearranged in the form

$$u_t^2 = (gH_t/B_{0_a})(\Delta T_0/T_{av})_t \tag{9}$$

For a given value of B_{0_a} and the test flow height H_t, Eq. (9) may be satisfied for various combinations of u_t and $(\Delta T_0/T_{av})_t$. However, a practically attainable maximum value** for the ratio $(\Delta T_0/T_{av})_t$ is about 0.1 (which corresponds to a value of ΔT_0 of about 30°C), so that Eq. (9) can be written in the form of an inequality as

$$u_t^2 \lesssim 0.1\, gH_t/B_{0_a} \tag{10}$$

This relation is plotted in Fig. 2 for various values of the parameter B_{0_a}. It may be noted that a typical maximum value of the parameter B_{0_a} in the atmosphere is of the order of unity.

The interpretation of the curves given in Fig. 2 is that, for each of the values of B_{0_a} shown, proper simulation is possible only in the region to the left of the curves. Thus for each value of B_{0_a}, the test envelope is given by the region bounded by the curves representing the limits of thermal simulation and aerodynamically rough flow. For example, if the maximum height of the attainable test flow were only 15 in. and the value of (H_a/z_{0_a}) equal to 1000, then complete simulation of thermal-stratification effects for values greater than B_{0_a} of 0.1 would be impossible and partial simulation would have to be resorted to. An optimum choice for the height of the test flow seems to be about 32 in., since this height would provide proper simulation down to velocities of 3 fps and up to values of B_{0_a} of about 0.6 and (H_a/z_{0_a}) of 1000 (which are adequate for most simulation purposes). A laboratory facility intended for simulating the turbulence characteristics of the lower atmosphere must be capable of producing the operating conditions just discussed.

The arguments just given should be regarded as providing guidelines for choosing the dimensions of an atmospheric simulation facility rather than providing rigorous criteria. Specifically, this analysis will be valid only under conditions of neutral and near-neutral stability since the simple logarithmic representation, given in Eq. (5), for the velocity profile will be valid only under these conditions. It should also be noted that when simulating strongly unstable flows experimental difficulties may be encountered due to the occurrence of secondary circulations in the laboratory facility.

Generation of a Model Atmospheric Surface Layer

It has been pointed out in the second section that the only portion of the atmosphere that can be modeled accurately in a wind tunnel is that portion which can be described entirely in terms of conditions specified at the surface. It follows that the model flow must also meet the aforementioned requirement in the testing region. In a boundary layer which has grown naturally over a long surface, this region is the constant shear stress layer and extends, at most, over the lower three-tenths of the boundary-layer thickness. Since the entire depth of a "naturally" grown boundary layer cannot be regarded as a suitable model for the atmosphere, it is of interest, even in this case, to increase the thickness of the constant flux layer by some artificial means.

It is clear that, in order to be able to exploit the full potential of wind-tunnel simulation of the atmospheric surface layer, one must be able to generate thick, constant-friction layers in the laboratory. Experimental work that has been performed at CAL on various techniques of generating flows which are good models of the neutrally stable atmosphere has resulted in a simple but promising technique of generating thick constant-stress layers. In this technique the flow on the wind-tunnel floor is "tripped" by a fence spanning the tunnel width and is then allowed to develop over a moderately long region of rough floor. It has been found that when the aerodynamic roughness of the floor is carefully

** Note that all the atmospheric flow theories use the Boussinesq approximation, namely that $(\Delta T_0/T_{av})_a \ll 1$.

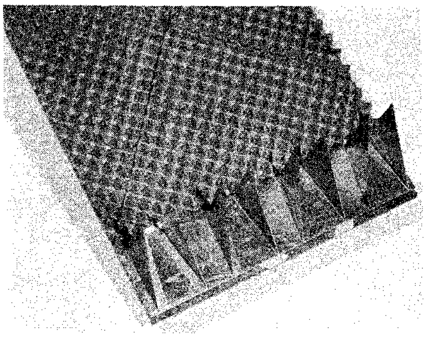


Fig. 3 View of vortex generators and rough ground.

matched to the fence height, flows with the desired characteristics are produced. These experiments are described in this section.

The experimental investigation was conducted in the microsonic leg of the CAL/Air Force High Speed Wind Tunnel. The inlet to this wind tunnel draws in ambient air from the surrounding room. The distance between the inlet and the beginning of the test section was varied by the insertion of extension sections made of plywood. A rough ground was simulated on the floor of the wind tunnel between the inlet and the rear portion of the test section. Provision was made for adjusting the height of the floor in sections three feet in length. This adjustment was used to maintain an approximately zero pressure gradient along the axis of the wind tunnel.

Roughness elements used on the ground were four-sided regular pyramids 0.75 in. in height and 0.75 in. along each side of the square base. A view of the roughness elements mounted on the ground board is shown in Fig. 3, as are the vortex generators used at one stage of the investigation. The choice of this particular type of roughness element was based on availability of suitable materials and has no other significance. With the rough ground installed, test section dimensions were 22.5 in. in height and 17 in. in width.

All velocity measurements were made with a Thermo Systems Inc. linearized crossed-hot-wire anemometer system. The crossed-wire probe was mounted in a traverse system which could be set with an accuracy of 0.001 in. relative to a known reference position. The crossed-wire probe was calibrated both for flow velocity sensitivity and flow angle sensitivity. The latter calibration was performed by pitching the probe through a range of angles while holding the flow velocity contant. Mean values of velocity were obtained from readings of the two linearized outputs. These outputs were averaged through a seven second time constant on each of the two meters. Fluctuating quantities were recorded on two channels of an Ampex FM type recorder. Data were recorded at 15 in./sec and later played back at 60 in./sec for reduction purposes. Corrections for the change in speed were applied when spectra were determined. In order to obtain consistent and repeatable results it was found necessary to supply a well regulated voltage to the tape recorder both in the record and playback modes. This was particularly true for the determination of shear stress which requires very high accuracy from the instrumentation since it involves the difference between

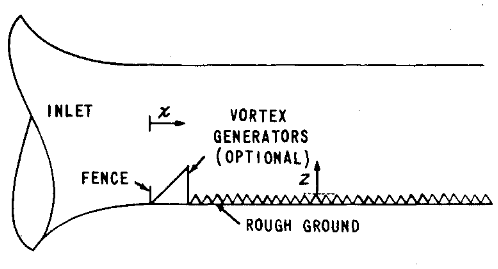


Fig. 4 Configuration tested for simulating a thick turbulent boundary layer on a rough ground.

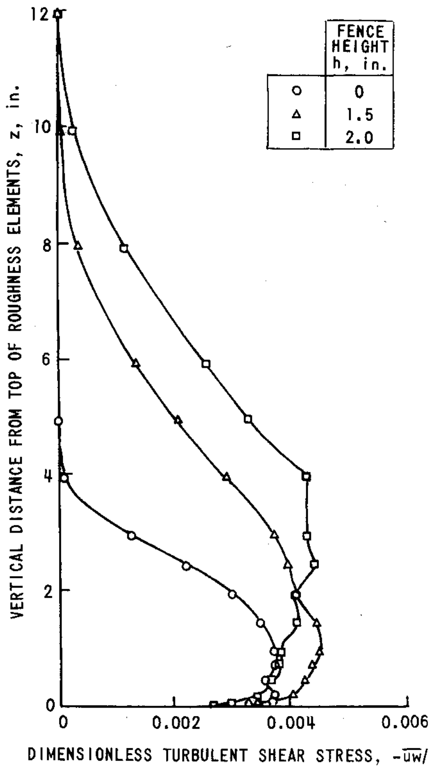


Fig. 5 Comparison of turbulent shear stress distribution above a rough surface preceded by a fence of various heights. Distance from fence, $x = 73.4$ in.

two large numbers (i.e., the difference in the mean squares of the two linearized outputs from the crossed-wire probe). With such voltage regulation, repeatable results were obtained.

The information extracted from the tape records consisted of turbulent shear stress, longitudinal and vertical turbulence intensity, and spectra of the longitudinal and vertical turbulence intensity. The root-mean-square and mean-square values of the signals were measured with a Thermo-Systems Inc. Model 1060 RMS voltmeter. Instantaneous sums and differences of the crossed-wire signals were obtained from a Model 1015 Correlator made by the same compoany. Spectra were obtained with the aid of a General Radio Type 1900 Wave Analyzer.

All measurements except frequency spectra were obtained at two lateral locations for two different distances from a fence followed by a rough surface (Fig. 4). Measurements were made with fence heights of 0, 1.5, and 2 in. spanning the wind-tunnel floor. For nonzero fence heights the investigation included cases with and cases without vortex generators situated immediately downstream of the fence (Fig. 3). In general, it was found that the vortex generators had no measurable effect on the flow at the downstream measuring stations and that the flow at the two lateral locations was the same to within the experimental accuracy. Hence, the results presented in the following paragraphs, which have been limited to measurements taken on the tunnel centerline and without the vortex generators in place, can be considered as representative of all of the measurements which were made. The freestream velocity u_∞ was approximately 40 fps for all tests.

The measured shear stress distributions at a distance of 73.4 in. from the fence location are shown for several fence heights in Fig. 5. Note that the shear stress for a fence height of 2 in. is nearly constant out to a distance of 4 in. The depth of the 4-in. constant shear-stress layer is approximately four times that of the constant shear-stress region found with the naturally developed flow. Moreover, there appears to be very little decay of the shear stress with distance downstream of the fence. This is illustrated in Fig. 6 where the shear-stress distributions measured at

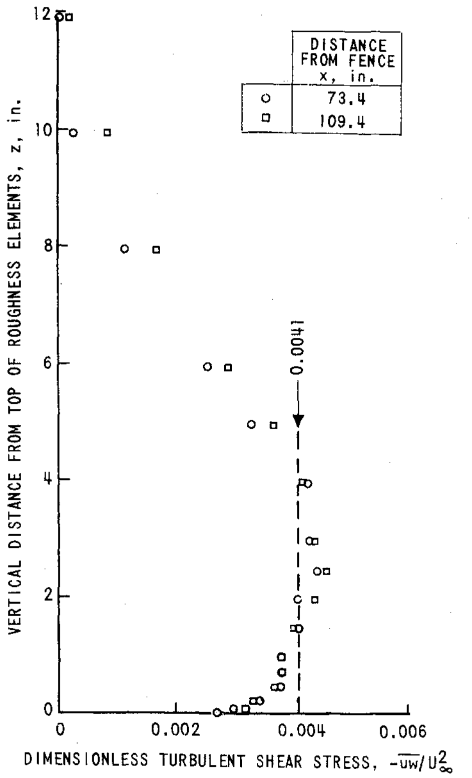


Fig. 6 Turbulent shear stress distributions above a rough surface preceded by a fence. Fence height = 2.0 in.

distances of 73.4 and 109.4 in. from the fence are compared to each other for a fence height of 2 in.

The vertical distribution of longitudinal and vertical turbulence intensity, $(\overline{u'^2})^{1/2}$ and $(\overline{w'^2})^{1/2}$ are shown in Fig. 7 for the natural boundary layer ($h = 0$), and for a fence height of 2 in. The intensities have been nondimensionalized by the mean wall friction velocity u_*, and the vertical coordinate by the roughness length z_0. It can be seen that the agreement between the natural and artificial boundary layers is excellent in the region where both flows have a nearly constant value of shear stress ($z/z_0 \lesssim 50$). The largest discrepancy is in $(\overline{u'^2})^{1/2}/u_*$ for a fence

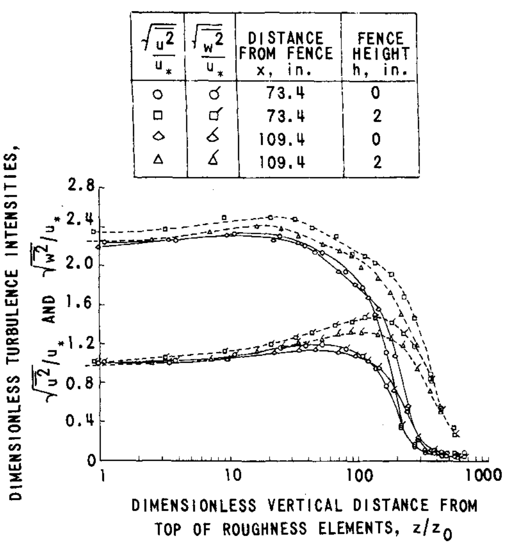


Fig. 7 Comparison of dimensionless turbulent intensity distributions above a rough surface with and without a fence at the start of the roughness.

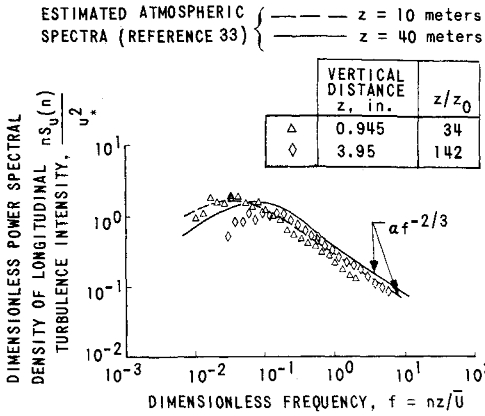


Fig. 8 Comparison of spectra of longitudinal turbulence intensity in fence generated flow with estimated spectra for the neutral atmosphere. Fence height $h = 2$ in. Distance from fence, $x = 109.4$ in.

height of 2 in. at 73.4 in. from the fence. Even these values are only about 10% higher than the corresponding values in the natural boundary layer. For values of (z/z_0) greater than 50 the increasing difference between the natural and artificial boundary layers is to be expected since the shear stress is no longer nearly constant in the natural boundary layers. In the artificial flow, the region of nearly constant shear stress extends to (z/z_0) values of between 150 and 200,†† that is 3 to 4 times the depth of the natural constant-shear region.

It is difficult to provide a definitive comparison between these intensity data and those found in the neutrally stable atmosphere since the latter scatter over a relatively wide range of values. A value of 1.3 has been advanced as a representative mean for $(\overline{w'^2})^{1/2}/u_*$ in Ref. 31. This is in reasonable over-all agreement with the data in Fig. 7 for the constant stress regions of the flow. Lettau and Davidson[32] give 1.10 as an average value of $(\overline{u'^2})^{1/2}/z\,(\partial u/\partial z)$ for the neutral atmosphere. From the law of the wall, $u/u_* = 2.5 \ln(z/z_0)$, one obtains

$$z\,(\partial u/\partial z) = 2.5u_*$$

whence $(\overline{u'^2})^{1/2}/u_* = 2.75$ is an average value in the neutral atmosphere. Again this value is in reasonable agreement with the model flow data in Fig. 7 considering the wide scatter of the full scale data. Also Lettau and Davidson[32] give a mean value of 0.36 for the ratio $(\overline{w'^2})^{1/2}/(\overline{u'^2})^{1/2}$. This gives a value of $(\overline{w'^2})^{1/2}/u_*$ of 0.99. The range 0.99 to 1.3 for $(\overline{w'^2})^{1/2}/u_*$ is in excellent agreement with the current data in the constant stress region.

In addition to the turbulent intensities themselves, spectra of longitudinal and vertical turbulent intensities have also been measured. These spectra for the fence generated flow are compared with estimated spectra for the neutrally stable atmosphere in Figs. 8 and 9, respectively. In each case, the atmospheric spectra shown have been given as representative of many measured cases. In Figs. 8 and 9, the power spectral density and the frequency have been nondimensionalized in the fashion in which the atmospheric data are usually presented. An alternate method of presenting the data, which has been used by Cermak,[21] is to normalize the power spectral density and the frequency by using the Kolmogorov velocity and length scales. The atmospheric longitudinal spectra were estimated from the data of Berman[33] for heights of 10 and 40 m. The high-frequency region of each curve has been extended with a straight line whose slope follows the law of the inertial subrange, $S(n) \sim n^{-5/3}$, as suggested by Berman (with the nondimensionalization used here, $nS(n)/u_*^2 \sim f^{-2/3}$ in the inertial subrange). The heights of 10 and 40 m were chosen to have approximately the same ratio as the heights used in the model

†† In more recent experiments over smaller scale ground roughness,[34] constant shear stress was found to extend to values of (z/z_0) up to approximately 600.

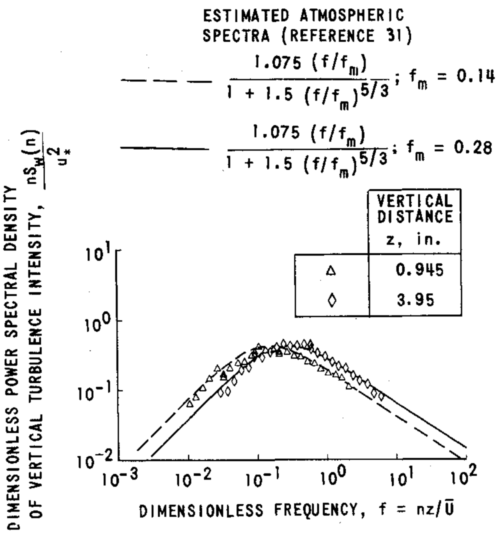


Fig. 9 Comparison of spectra of vertical turbulence intensity in fence-generated flow with estimated spectra for the neutral atmosphere.

flow. The agreement between the model and atmospheric spectra is reasonable bearing in mind the scatter of the full-scale data.

The estimated atmospheric spectra of the vertical turbulence intensity shown in Fig. 9 were constructed from the expression

$$nS_w(n)/u_*^2 = 1.075(f/f_m)/[1+1.5(f/f_m)^{5/3}]$$

where f_m is the value of f at the maximum. This expression was advanced by Busch and Panofsky[31] as a reasonably good fit to the neutral atmosphere except at the low frequencies where the energy is systematically underestimated. They suggested a value of f_m of approximately 0.32 as representative of neutral and unstable air. It can be seen from Fig. 9 that curves constructed from the preceding expression provide an excellent fit to the model-flow spectra although the peak for $z = 0.945$ occurs at a value $f_m = 0.14$ which is lower than the suggested value of 0.32. (The difference between 0.32 and the value $f_m = 0.28$ found for $z = 3.95$ is insignificant.) It is noted in Ref. 31 that the value of f_m in the atmosphere increases with height above a height of 50 m. Below 50 m, the available evidence apparently indicates little change in f_m with height. The value of 0.32 for f_m then would appear to be a minimum for the neutral and unstable atmosphere whereas the model flow reached the value above of approximately 0.14 close to the ground. It is not known whether this difference is significant. However, it is worth noting that the natural boundary layer was found to be similar[15] to the artificially generated model flow for a height $z = 0.945$ in. Hence, the natural boundary layer represents no improvement over the fence generated flow very close to the ground where both flows exhibit a nearly constant shear stress. Farther from the ground, but still in the constant shear stress region of the artificial flow, the spectrum of the vertical turbulence in the artificial flow is in excellent agreement with atmospheric spectra.

Concluding Remarks

This paper has presented some theoretical and experimental results on the laboratory simulation of the atmospheric surface layer. It was pointed out that the simulation of horizontally-homogeneous, thick, constant-stress layers is a necessary prerequisite to simulating more complex atmospheric flows. The conditions of horizontal homogeneity and constancy of shear stress assure that the initial distributions of velocity and turbulence statistics in the laboratory flow are the same as the initial distributions for the corresponding atmospheric flow. It was shown that the various similitude criteria can be used to deduce the operating requirements for a laboratory facility for the simulation of atmospheric turbulence.

The extent to which various laboratory flows meet the similitude requirements was investigated experimentally. In particular, the flow downstream of a flat-plate fence followed by a length of rough ground was investigated to determine its suitability as a model of the neutrally stable atmospheric surface layer. The flow properties investigated were vertical distributions of mean velocity, turbulent shear stress, and longitudinal and vertical turbulence intensity. Spectra of the longitudinal and vertical turbulence intensities were also obtained at selected heights above the rough ground. These data were compared with data obtained in a boundary layer generated naturally (no fence) over the same rough ground and with measurements made in the neutrally stable atmosphere where possible.

It was found that the fence-generated flow could be "matched" to the rough ground by proper choice of fence height so as to provide a region near the ground of nearly constant shear stress which was three to four times as thick as that in a natural boundary layer, and which did not change measurably with distance downstream. In regions where both the natural and artificial boundary layers exhibited nearly constant shear stress, the remaining properties of the natural and artificial flow exhibited similarity. Comparison of the turbulence intensities and spectra of the turbulence intensities for the fence generated flow with atmospheric data showed relatively good agreement in the constant shear stress region.

The data reported herein are restricted to neutral flow. Specifically, the simulation in nonadiabatic flows was not investigated. The similitude criteria that have to be satisfied to model nonadiabatic atmospheric flows in the laboratory have been set forth in Ref. 8 where it has been shown that one of the prerequisites for simulation of the surface layer is that the heat flux must be constant over the depth of the laboratory test flow. Thick, constant heat flux layers can be generated in the laboratory by a concentrated heat addition at some axial station of the test section of the laboratory simulation facility, in a manner that is entirely analogous to the generation of thick constant shear layers by a concentrated addition of momentum. Again, as in the case of the generation of the constant shear layer, the thickness of the constant heat flux layer (downstream of the point of heat addition) can be maintained nearly constant only if a suitably chosen, distributed heat addition is used along the ground downstream of the point of heat addition.

It is our firm belief that laboratory simulation of the atmospheric surface layer can contribute greatly towards understanding some of the complex processes taking place in it. In the study of the atmospheric surface layer, it is highly desirable to arrive at a state similar to that currently existing in aerodynamics, with modeling and full-scale testing existing side by side, each complementing the other. In spite of the considerable progress that has been made, the unsolved problems and difficulties that remain ahead cannot be belittled. It is unrealistic to insist that the current state of atmospheric modeling is advanced enough to be able to simulate all the complex facets of the structure and motions of the atmosphere. Experience has shown that certain essential portions of the atmosphere, such as the surface layer or the constant friction layer, can indeed be modeled accurately in a laboratory boundary layer. Experience has also shown that it is not sufficient to simulate the mean-velocity profile alone, as has been done often in laboratory studies of atmospheric wind problems; proper simulation of the turbulence characteristics of the surface layer is essential.

References

[1] Schlichting, H., *Boundary Layer Theory*, 1st ed., McGraw-Hill, New York, 1955, pp. 400–429.

[2] Sutton, O. G., *Micrometeorology*, McGraw-Hill, New York, 1953.

[3] Sherlock, R. H. and Stalker, E. A., "The Control of Gases in the Wakes of Smoke Stacks," *Mechanical Engineering*, Vol. 62, No. 6, June 1942, pp. 455–458.

[4] von Hohenleiten, H. A. and Wolf, E. F., "Wind Tunnel Test to Establish Stack Height for Riverside Generating Stations," *Transactions of the ASME*, Vol. 64, No. 10, Oct. 1942, pp. 671–683.

[5] Hewson, W. E., "Atmospheric Pollution," *Compendium of Meteorology*, American Meteorological Society, Boston, 1951.

[6] Cermak, J. E. et al., "Simulation of Atmospheric Motion by Wind-Tunnel Flows," Technical Report CER66JEC-VAS-EJP-GJB-HC-RNM-SI17, May 1966, Fluid Dynamics and Diffusion Lab., Colorado State Univ., Fort Collins, Colo.

[7] Hidy, G. M., ed., "On Atmospheric Simulation: A Colloquium," NCAR-TN-22, Nov. 1966, National Center for Atmospheric Research, Boulder, Colo.

[8] McVehil, G. E., Ludwig, G. R., and Sundaram, T. R., "On the Feasibility of Modeling Small Scale Atmospheric Motions," CAL Rept. ZB-2328-P-1, April 1967, Cornell Aeronautical Lab., Buffalo, N.Y.

[9] Strom, G. H. and Halitsky, J., "Important Considerations in the Use of Wind Tunnels for Pollution Studies of Power Plants," *Transactions of the ASME*, Vol. 77, No. 6, Aug. 1955, pp. 789–795.

[10] Arya, S. P. S. and Plate, E. J., "Modeling of the Stably Stratified Atmospheric Boundary Layer," *Journal of Atmospheric Science*, Vol. 26, No. 4, July 1969, pp. 656–665.

[11] Cermak, J. E. and Arya, S. P. S., "Problems of Atmospheric Shear Flows and Their Simulation," *AGARD Conference Proceedings No. 48*, 1970, pp. 12.1–12.16.

[12] Halitsky, J., "Validation of Scaling Procedures for Wind Tunnel Model Testing Diffusion Near Buildings," TR-69-8, Dec. 1969, Geophysical Sciences Lab., New York Univ., New York.

[13] Plate, E. J. and Quraishi, A. A., "Modeling of Velocity Distributions Inside and Above Tall Crops," *Journal of Applied Meteorology*, Vol. 4, No. 3, June 1965, pp. 400–408.

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

[15] Ludwig, G. R. and Sundaram, T. R., "On the Laboratory Simulation of Small-Scale Atmospheric Turbulence," CAL Rept. VC-2740-S-1, Dec. 1969, Cornell Aeronautical Lab., Buffalo, N.Y.

[16] Sundaram, T. R., Skinner, G. T., and Ludwig, G. R., "Simulation of Small-Scale Atmospheric Phenomena," CAL Rept. VC-2697-A-1, April 1970, Cornell Aeronautical Lab., Buffalo, N.Y.

[17] Ellison, T. H., "Turbulent Transport of Heat and Momentum from an Infinite Rough Plane," *Journal of Fluid Mechanics*, Vol. 2, No. 5, July 1957, pp. 456–466.

[18] Monin, A. S. and Obukhov, A. M., "Basic Regularity in Turbulent Mixing in the Surface Layer of the Atmosphere," *USSR Academy of Sciences, Works of Geophysics and Meteorology*, Vol. 151, No. 24, 1954, p. 163.

[19] Lettau, H. H., "Wind Profile, Surface Stress, and Geostrophic Drag Coefficients in the Atmospheric Surface Layer," *Atmospheric Diffusion and Air Pollution*, Academic Press, New York, 1959, pp. 241–257.

[20] Ellison, T. H., "Atmospheric Turbulence," *Surveys in Mechanics*, Cambridge University Press, Cambridge, 1956, pp. 400–430.

[21] Cermak, J. E., "Laboratory Simulation of the Atmospheric Boundary Layer," *AIAA Journal*, Vol. 6, No. 9, Sept. 1971, pp. 1746–1754.

[22] Davenport, A. G., "An Approach to Wind-Tunnel Modeling of the Response of Structures to the Natural Wind," *Proceedings of the Meeting on Ground Wind Load Problems in Relation to Launch Vehicles*, NASA Langley Research Center, June 7–8, 1966, pp. 12.1–12.13.

[23] Schon, J. P. and Kreiss, I., "Evolution des Caractêristiques Moyennes et Turbulentes dans Une Couche Limite Soufflée," EDG 1969, Laboratorie de Mêcanique de Fluides, Ecole Centrale Lyonnaise, Lyons, France.

[24] Templin, R. J., "Interim Progress Note on Simulation of Earth's Surface Winds by Artificially Thickened Wind Tunnel Boundary Layers," Rept. LTR-LA-22, 1969, National Aeronautical Establishment, Ottawa, Canada.

[25] Counihan, J., "A Method of Simulating a Neutral Atmospheric Boundary Layer in a Wind Tunnel," *AGARD Conference Proceedings No. 48*, 1970, pp. 14.1–14.13.

[26] Cockrell, D. J. and Lee, B. E., "Methods and Consequences of Atmospheric Boundary Layer Simulation," *AGARD Conference Proceedings No. 48*, 1970, 13.1–13.14.

[27] Calder, K. L., "Concerning the Similarity Theory of A. S. Monin and A. M. Obukhov for the Turbulent Structure of Thermally Stratified Surface Layer of the Atmosphere," *Quarterly Journal of the Royal Meteorological Society*, Vol. 92, No. 391, Jan. 1966, pp. 141–146.

[28] Davenport, A. G. and Isyumov, N., "The Application of the Boundary Layer Wind Tunnel to the Prediction of Wind Loading," *Wind Effects on Buildings and Structures*, Vol. 1, University of Toronto Press, Toronto, Canada, 1967, pp. 201–230.

[29] Cermak, J. E., "Determination of Wind Loading on Structural Models in Wind-Tunnel Simulated Winds," *Proceedings of the Symposium on Wind Effects on High-Rise Buildings*, Northwestern Univ., Evanston, Ill., March 1970, pp. 61–88.

[30] Jensen, M., "The Model-Law for Phenomena in Natural Wind," *Ingeniren-International Edition*, Vol. 2, No. 4, 1958, pp. 121–128.

[31] Busch, N. E. and Panofsky, H. A., "Recent Spectra of Atmospheric Turbulence," *Quarterly Journal of the Royal Meteorological Society*, Vol. 94, No. 400, April 1968, pp. 132–148.

[32] Lettau, H. H. and Davidson, G., ed., "Exploring the Atmosphere's First Mile," *Proceedings of the Great Plains Turbulence Field Program*, Vol. 1, Instrumentation and Data Evaluation, Pergamon Press, New York, 1957.

[33] Berman, S., "Estimating the Longitudinal Wind Spectrum Near the Ground," *Quarterly Journal of the Royal Meteorological Society*, Vol. 91, No. 389, July 1965, pp. 302–317.

[34] Ludwig, G. R., Sundaram, T. R., and Skinner, G. T., "Laboratory Modeling of the Atmospheric Surface Layer with Emphasis on Diffusion," CAL Rept. VC-2740-S-2, July 1971, Cornell Aeronautical Lab., Buffalo, N.Y.