Critical Review of Wind Tunnel Modeling of Atmospheric Heat Dissipation

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CRITICAL REVIEW OF WIND TUNNEL
MODELING OF ATMOSPHERIC HEAT DISSIPATION

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SUMMARY

There is increasing concern by scientists that future proposed energy or power parks may significantly affect the environment by releasing large quantities of heat and water vapor to the atmosphere. This report presents a critical review of the potential application of physical modeling (wind tunnels) to assess possible atmospheric effects from heat dissipation systems, such as, cooling towers. A short inventory of low-speed wind tunnel facilities is included in the review.

The useful roles of wind tunnels are assessed and the state-of-the-art of physical modeling is briefly reviewed in the report. Similarity criteria are summarized and present limitations in satisfying these criteria are considered. Current physical models are defined and limitations are discussed.

Three experimental problems are scoped in which physical modeling may be able to provide data. These are,

- 1) defining the critical atmospheric heat load;
- 2) topographic and local circulation effects on thermal plumes; and
- 3) plume rise and downstream effects.

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CRITICAL REVIEW OF WIND TUNNEL MODELING OF ATMOSPHERIC HEAT DISSIPATION

M. M. Orgill

USEFUL ROLES OF WIND TUNNELS

Wind tunnels have not been used very extensively in studying heat dissipation systems because of the difficulties in matching the necessary similarity criteria and in modeling a composite of thermal and mechanical turbulence. However, during the past few years a number of experiments have been conducted in relation to this problem and the results appear to be encouraging. These recent studies indicate that wind tunnel experiments on heat dissipation systems may produce useful results for the present AENEC (Atmospheric Effects of Nuclear Energy Centers) program.

If one examines the research needs (Carson, 1975) for dry and wet cooling systems, that may be utilized in power parks or nuclear energy centers, at least eight problems can be identified that wind tunnel experiments could possibly provide useful and practical information in which to assess atmospheric effects. These problems can be defined as,

- 1) determining the critical atmospheric heat load of a given site or defining the critical heat load in which a power park may create its own mesocirculation or interact significantly with the surrounding environment;
- 2) evaluating the heat island characteristics of power parks;
- 3) determining whether multiple cooling units can enhance the development of atmospheric vortices;

- 4) estimating plume motion in complex terrain and in local circulations (sea and lake breezes, etc.);
- 5) estimating plume rise and dimensions under certain environmental conditions;
- 6) estimating plume touchdown distances during certain environmental conditions;
- 7) determining structure or building wakes, aerodynamic downwash, and optimum siting of towers, buildings, etc., and
- 8) estimating the merging of multiple cooling tower plumes.

The greatest benefits of wind tunnel experimental results probably occurs before a particular project, e.g., power park has reached the construction stage. Experimental results from wind tunnel simulations could point out possible problems that could be corrected before the facility is actually constructed. This could eliminate costly modifications or resultant consequences.

When a power park already exists then wind tunnel simulations on the various problems outlined above could result in valuable information that could be compared with mathematical and liquid models and field data. The experimental results would also be of value in aiding field programs and planning field operations.

STATE-OF-THE-ART

Several difficulties arise in attempting to generate a satisfactory physical (wind tunnel) model which will be similar to the actual atmospheric boundary layer. The principal difficulties are due to the limitations of a stationary laboratory facility in reproducing all the complex features of a scaled-down atmospheric boundary layer.

The problem requires not only a simplification of the basic mathematical equations of the atmosphere by a set of restrictive assumptions, but for correct simulation certain nondimensional parameters should be satisfied by the physical model. Almost invariably, the assumptions and duplication of the nondimensional parameters are not completely satisfied. Hence, a decision must be made as to which parameters are dominant and relax the requirements on the least important ones. This difficult decision will depend to a certain extent upon the length scale of the problem interested in or required to use because of the nature of the problem.

SIMILARITY REQUIREMENTS FOR THE ATMOSPHERIC BOUNDARY LAYERS

Physical modeling of the atmospheric boundary layer by wind tunnels requires geometric, kinematic, dynamic, and thermal similarity and similarity of boundary conditions. This means that the flow and thermal characteristics of the model and prototype systems should be described by the same mathematical equations even though appropriate adjustments of air flow velocity, temperature and other variables are necessary for the model.

The basic equations necessary for considering atmospheric motions and dispersion are the following:

- Equations of motion
- Continuity equation
- Equation of state
- Poisson's equation
- Equation of turbulent heat transfer
- Equation of heat transfer from the surface boundary,
and
- Parabolic diffusion equation.

In similarity analysis the continuity equation, equation of state and Poisson's equation do not contribute any important nondimensional parameters and are omitted from further analysis. Therefore, the principal equations to be considered in determining similarity criteria are:

Equations of Motion

$$\frac{\partial \bar{u}_i}{\partial t} + \bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} + 2\epsilon_{ijk} \Omega_j \bar{u}_k = - \frac{1}{\rho} \frac{\partial \bar{p}}{\partial x_i} + \frac{1}{\rho} \frac{\partial \bar{\sigma}_{ij}}{\partial x_j} + \frac{1}{\rho} \frac{\partial \sigma_{ij}}{\partial x_j} - \frac{\Delta \bar{T}}{\bar{T}} g \delta_{i3}$$

Equation of Turbulent Heat Transfer

$$\rho C_p \left(\frac{\partial \bar{T}}{\partial t} + \bar{u}_j \frac{\partial \bar{T}}{\partial x_j} \right) - \frac{\partial \bar{p}}{\partial t} - \bar{u}_j \frac{\partial \bar{p}}{\partial x_j} - \overline{u'_j \frac{\partial p'}{\partial x_j}} = \frac{\partial}{\partial x_j} \left(\kappa \frac{\partial \bar{T}}{\partial x_j} \right) - C_p \rho \frac{\partial}{\partial x_j} (\overline{T' u'_j}) + \bar{\phi}$$

Equation of Heat Transfer from the Surface Boundary

$$Q_T - Q_R + Q_{L\downarrow} - Q_{L\uparrow} = \pm Q_G \pm Q_H \pm Q_E$$

Parabolic Diffusion Equation

$$\frac{\partial \bar{C}}{\partial t} + \frac{\partial}{\partial x_i} (\bar{C} \bar{V}_i) = \frac{\partial}{\partial x_i} K_{ii} \frac{\partial \bar{C}}{\partial x_i} + k_m \frac{\partial^2 \bar{C}}{\partial x_i \partial x_i}$$

The above equations are subject to a number of restrictive assumptions. These are,

- 1) the atmosphere is composed of a perfect gas of constant composition,

- 2) the deviation of pressure, temperature, and density are small compared with the neutral values,
- 3) the density is independent of the fluctuating pressure (Small Mach number),
- 4) variation of ν and κ are negligible,
- 5) the generation of heat through viscous stresses is negligible, and
- 6) there are no sources or sinks of any kind.

With these assumptions a number of less important terms such as $\bar{\Phi}$ and various pressure terms are dropped from the above equations.

The necessary nondimensional parameters can be obtained by three methods: inspectional analysis of the above governing equations, dimensional analysis and similarity theory. Various derivations are found in articles and publications such as, McVehil, et al. (1967), Nemoto (1961a, 1962), Bernstein (1965), Strom (1966), Cermak (1971), Orgill (1971, 1972), and Synder (1972). The following outline indicates, in general, what similitude requirements are necessary for complete flow and thermal similarity.

Boundary Conditions

Upstream conditions - initial velocity, turbulence,
temperature profiles

Upper-level conditions - temperature inversions

Lower boundary conditions - surface topography or
structures

Side boundary conditions - topography and wind-tunnel
wall effects

Geometric Similarity

Terrain or structure features, roughness, trees

Boundary-layer thickness

Kinematic Similarity

Streamlines or trajectories

Velocity profiles

Dynamic and Thermal Similarity

Rossby number $Ro = U_R / L \Omega_R$

Reynolds number $Re = U_R L / \nu$ $Re_t = U_R L / K_R$

Froude number $F_r = U_R / (gL \Delta T_R / \bar{T})^{1/2}$

Prandtl number $Pr = \nu / \kappa$

or

Peclet number $Pe = U_R L / \kappa$

Dispersion Similarity

Schmidt number $Sc = \nu / k_m$

or

Peclet number $Pe = U_R L / k_m$

Some alternative dimensionless parameters which result from the buoyancy term are,

Richardson number $Ri = g \frac{\Delta \bar{T}_R}{\bar{T}} \frac{L}{(\Delta U_R)^2}$

Grashof (or Rayleigh) number $GR = g L^3 \frac{\Delta \bar{T}_R}{\nu^2 \bar{T}}$

The Richardson number is also related to the Monin-Obukhov length,

$$L = u_*^3 C_p \rho \bar{\theta} / \kappa g Q_H$$

The equation of heat transfer from the surface boundary has normally been ignored in similarity analysis since the affects of the short, long and reflected radiation and the various heat fluxes have been neglected in most studies. However, recent model studies of urban heat islands have utilized the Monin-Obukhov length (sensible heat flux) as a similarity criteria (Sethuraman and Cermak, 1974).

It is well know that it is impossible to strictly satisfy all the above similarity criteria in wind tunnel studies. Generally, it is necessary that some of the criteria be relaxed. Therefore, it is of interest to briefly review the principal nondimensional parameters as to their limits in achieving similarity.

SIMILARITY CRITERIA

Rossby Number

The Rossby number describes the relative importance of the Coriolis acceleration

$$(2\epsilon_{ijk}\Omega_j\bar{U}_k)$$

when compared with advective, or local accelerations

$$\left(\bar{U}_j \frac{\partial \bar{U}_i}{\partial x_j}\right) .$$

If the Rossby number is large, Coriolis accelerations are small and local accelerations predominate in the flow.

To date all investigators have assumed the Rossby number to be large or have justified neglecting it as a criterion for modeling. Synder (1972) indicates that Rossby number effects may become important around 5 km for modeling atmospheric diffusion in relatively flat terrain. This criterion has been

relaxed in case of problems with complex terrain where local accelerations due to terrain may predominate. However, no cut-off point on distance has been rigorously defined in this case.

Reynolds Number

The Reynolds number represents the ratio of inertial

$$\left(\bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} \right)$$

to viscous

$$\left(\frac{1}{\rho} \frac{\partial \bar{\sigma}_{ij}}{\partial x_j} \right)$$

forces. In general, it is not possible to obtain strict Reynolds number equality for the model and the real atmosphere. In the atmosphere a typical value of the Reynolds number may be $Re \sim 10^{10}$ while for the model it may be $Re \sim 10^4$. Various ideas have been presented to attempt to justify the neglect of strict Reynolds number similarity. These ideas have been divided into three general categories; Reynolds number independence, turbulence scaling and laminar flow analogy (Synder, 1972).

Several investigators have used the concept of Reynolds number independence. To date, there exists a large amount of experimental evidence to support the theory. The approach is basically that in absence of thermal and Coriolis effects the flow structure and turbulence are similar over a very wide range of Reynolds numbers or the flow is essentially independent of the Reynolds number. The idea has been used extensively in modeling flow around sharp-edged geometry such as buildings or complex terrain.

The turbulence scaling idea was proposed by Nemoto (1961a). If thermal and Coriolis effects are negligible, then the mean

flow patterns of both model and prototype would be similar if the turbulent structure of the two flows were similar, e.g., if the turbulent Reynolds number and turbulent intensities of the two flows were identical. Two assumptions are made:

- 1) the turbulence of both model and prototype flows are "locally isotropic",
- 2) the Kolmogoroff velocity and microscale characterize the turbulence at each point in the flow.

The first assumption is satisfied if the Reynolds number is large but the second assumption may not be satisfied for length scale reductions of 1:300 to $1:10^3$ (Synder, 1972).

The laminar flow analogy first proposed by Abe (1941) and used by Cermak and others (1971) attempts to model the turbulent prototype flow with a laminar model flow with thermal stability. A turbulent Reynolds number is equated with the usual Reynolds number

$$(\text{Re})_{\text{model}} = \frac{U_R L}{\nu} = (\text{Re}_t)_{\text{prototype}} = \frac{U_R L}{K_R} \quad .$$

Since K_R/ν is on the order of 10^3 and if the scale ratio is on the order of $1:10^3$, then similarity may be established between the two flows. This type of similarity may be roughly correct for very stable situations and case where the advective transport (mean flow) may predominate. However, the concept is not strictly correct because the kinematic viscosity being a fluid property is not an adjustable parameter while the turbulent eddy viscosity (K_{ij}) may vary with height, stability, and direction.

Froude Number

The square of the Froude number represents the ratio of inertial

$$\left(\bar{U}_j \frac{\partial \bar{U}_i}{\partial x_j} \right)$$

to buoyancy

$$\left(\frac{-\Delta \bar{T}}{\bar{T}} g_{i3} \right)$$

forces. A large value of the Froude number implies that buoyancy forces are small compared to inertial forces.

It is well known that the Froude and Reynolds number can not be matched simultaneously. Froude number similarity requires decreasing the mean flow speed while the Reynolds number similarity requires increasing the mean flow speed. This conflict is sometimes resolved by matching the Froude number while insuring that a Reynolds number independent flow is established. This is not always possible. Yet, Batchelor (1953) has discussed the conditions under which the Froude number is the sole governing criterion for dynamical similarity of motion of a perfect gas atmosphere.

Prandtl, Peclet and Schmidt Numbers

The Prandtl and Schmidt numbers are fluid properties and not flow properties. The Prandtl number is the ratio of the momentum diffusivity (kinematic viscosity) to the thermal diffusivity. The Schmidt number is the ratio of the momentum diffusivity to mass diffusivity.

For air, the Prandtl number does not vary strongly with temperature so is generally the same in model and prototype, and if the Reynolds number are the same, the Peclet number criterion would be satisfied. Similarly the Schmidt number is nearly the same in model and prototype. However, the basic problem in matching of Peclet or Schmidt number, is not in the Prandtl or Schmidt numbers, but rather in the Reynolds number. Generally, the Peclet and Schmidt numbers may be neglected as modeling criteria if the flow exhibits Reynolds number independence.

Additional similarity criteria will be necessary if modeling effluent characteristics from tall stacks or towers is the problem. Strom (1966), Sundaram (1967), Murthy (1970), and Bogh (1975) have discussed the necessary similarity criteria. For approximate simulation of plumes it is necessary to preserve the following effects in the model and full scale,

- 1) the momentum ratio or the ratio of efflux velocity to ambient wind speed should be the same,
- 2) the ratio of the effluent temperature (density) at the source to the temperature of ambient air stream should be the same, and
- 3) the relative roles of initial momentum and initial buoyancy should be the same.

CURRENT PHYSICAL (WIND TUNNEL) MODELS

At the present time three general types of atmospheric air flow can be simulated by special wind tunnels or laboratory facilities with some degree of reality. These are 1) a forced-convection air flow, 2) stably-stratified air flow, and 3) inversion-capped free convection air flow.

Forced Convection (neutral) Air Flow

Froude number similarity is not essential for this air flow since the static stability is assumed neutral (isothermal for the model) and the pressure and flow field is generally determined by the geometry such as, roughness, terrain or buildings. At high Reynolds number the flow is essentially independent of Reynolds number similarity. In a few studies attempts have been made to match the model and prototype turbulent Reynolds numbers and other turbulence parameters (Nemoto, 1961b, Orgill, 1971).

This type of model air flow has been used in wind tunnel studies since the pioneering efforts of Field and Warden

(1929-30). Numerous laboratory studies on buildings, complex terrain, diffusion and the atmospheric surface boundary layer has applied this type of modeling.

Stably-Stratified Air Flow

Froude number similarity is essential for this type of model air flow since it attempts to model a stable temperature stratification in the atmosphere, i.e., an increase of potential temperature with height. Generally, Reynolds number similarity is not satisfied except by the laminar flow analogy or Reynolds number independence. Examples of this type of flow simulation are provided by Abe (1941), Cermak (1966), and Lin and Binder (1967).

Inversion-Capped Free Convection (unstable) Air Flow

Froude (Richardson) number, Grashof (Rayleigh) number, or Monin-Obukhov length simulation is essential for this model air flow. This is probably the most difficult air flow to simulate because strict simulation requires modeling a composite of mechanical and thermal turbulence. A few investigations have been conducted in water laboratory facilities where simulating the Reynolds number is slightly better than in a wind tunnel (Fanaki, 1971; Willis and Deardorff, 1975).

A variation of this model air flow has been applied to simulating air flow and diffusion over urban heat islands (Chaudhry and Cermak, 1971; Sethuraman and Cermak, 1974), heated-island gravity waves (Yamada and Meroney, 1974), air flow and diffusion in complex terrain (Orgill, 1971), and sea breeze effects (Ogawa, et al., 1975).

INVENTORY OF WIND TUNNEL FACILITIES

An inventory of potentially useful wind tunnel facilities for studying atmospheric effects of heat dissipation systems is given in Appendix A. The list is not comprehensive but should include all major wind tunnel facilities in the United States and Canada. The list is incomplete in regard to a world survey of wind tunnel facilities. This survey utilized information from other surveys that have been published by Synder (1974), Hunt and Fernholz (1975), and Nee (1975). Some information was interchanged with Flow Research Inc. who was also making a current wind tunnel and liquid facility survey. S. A. Anderson from Texas A&M was also currently surveying wind tunnel facilities, but this information was not available for this survey.

A large number of wind tunnel facilities for the study of atmospheric simulation problems exists throughout the world. A major part of these facilities are concentrated in western Europe, Japan, United States, and Canada. A number of locations have more than one facility, e.g., Colorado State University has four wind tunnel facilities in which at least three could be applied to the heat dissipation problem.

Many other facilities in the United States and Canada have been active in atmospheric simulation problems such as, New York University, University of Michigan, Calspan Corp., University of Notre Dame, University of Utah, Illinois Inst. of Technology, University of Western Ontario and National Research Council. A number of relatively new tunnels and groups are becoming active in this area such as the laboratory facility of the Environmental Protection Agency (Synder, 1974).

A number of laboratory facilities are active in England, France and other countries of Europe. The English groups have been particularly active in simulating the neutral atmospheric

surface boundary layer (Lloyd, 1967; Armitt and Counihan, 1968; Cook, 1973; Counihan, 1969, 1973). Recently, wind tunnel experiments were conducted at Zurich, Switzerland, on models of four different European cooling tower facilities (Bogh, 1975). Wind tunnel experiments on atmospheric flow problems have been active in Japan since the pioneering efforts of Abe (1941).

The variety of wind tunnel facilities is extremely wide but most of the laboratories have provisions for generating thick boundary layers with the proper mean velocity profile and turbulence structure. Some facilities have built in capabilities for producing stably-stratified and free convection air flow. Differential cooling or heating of the floor of the test section is commonly used in wind tunnels to produce these conditions. Although, other methods have shown some promise in creating fairly realistic free-convection air flow (Orgill, 1971; Chaudhry and Cermak, 1971).

A typical facility applicable to the three-dimensional heat dissipation problem should be a low-speed (0 to 10 m sec^{-1}), open-return wind tunnel having a test section of about 2 meters wide (or more), height 2 meters, and approximately 12 meters long. The facility should have provisions for producing free-convection air flow by floor heating or by other methods, be able to produce a thick ($>30 \text{ cm}$) boundary layer, and proper upstream boundary conditions in regard to velocity, temperature and turbulence profiles.

The larger wind tunnel facilities would probably be most appropriate for studying the heat dissipation problem but some of the smaller facilities could also be utilized if two-dimensional aspects of heat dissipation systems were of interest to the AENEC program.

Many of the wind tunnel facilities listed in Appendix A should satisfy most if not all of the above criteria. Details on the operational aspects of the various wind tunnels would

take up too much space to include in this survey, but much of this information can be found in the references of Synder, Hunt and Fernholz, Nee and others.

SCOPING EXPERIMENTAL PROGRAMS

If one examines the potential atmospheric problems of power parks in which wind tunnels may assume a useful role, at least, three types of problems can be defined that could be simulated in a laboratory facility. One, attempting to define the critical atmospheric heat load of a power park; two, evaluating topographic or local circulation effects on a power park thermal plume; and three, evaluating plume rise, structure wakes and other downstream effects. The first two problems would be concerned with the larger-scale aspects of power parks while the other problem would be concerned with smaller scale features.

CRITICAL ATMOSPHERIC HEAT LOAD

One of the experimental programs could consider defining the critical atmospheric heat load of a power park as far as interacting significantly with its surrounding environment. Also, the heat island characteristics and the possibility of power park thermal plumes generating atmospheric vortices could also be studied within this program.

Proposed power parks may cover a land area of around 5 to 100 km², therefore, this problem would probably require scale reductions of 1:10³ or more. One probable serious simulation problem would be the matching of Rossby numbers between the field and model or alternatively simulating wind directional shear in the laboratory facility. The selected laboratory investigators would have to justify neglecting wind-directional shear effects or seriously consider modifying or constructing a facility that could simulate these effects.

The present modeling techniques should presumably be sufficient enough to generally satisfy the typical Reynolds, Froude, Grashof, and Peclet (Prandtl) similarity, however, it will be important that boundary conditions especially upstream velocity, temperature and turbulence profiles can be varied enough to represent a reasonable selection of conditions from the real atmosphere.

TOPOGRAPHIC AND LOCAL CIRCULATION EFFECTS

This experimental program would only be required if power parks were to be constructed in or near very complex terrain or near locations affected by local circulations (sea and lake breezes). The simulation experiments would be in regard to how complex terrain features or local circulations may affect the thermal plume trajectory and also how the plume interacts with the surrounding ambient environment.

Scale reductions would be on the order of $1:10^3$ and probably $1:10^4$ depending on the area of interest. Again, Rossby number simulation will have to be seriously considered especially in the case of local circulations such as the sea or lake breeze.

PLUME RISE AND DOWNSTREAM EFFECTS

The third experimental problem would concern plume rise from single or multiple cooling towers, cooling tower wakes and downstream effects, multiple plume merging, and plume touch-down.

Scale reductions would be between $1:10^2$ and $1:10^3$. It's at this scale range where wind tunnel facilities can probably provide a lot of useful and practical information. Rossby number matching between model and field is generally not required and the other similarity criteria can usually be satisfied to a reasonable degree. Accurate boundary conditions in

relation to geometry of structures and upstream air flow condition is very important at this scale.

The three experimental programs just outlined above could probably be done at one good single wind tunnel facility or could be divided between two or three laboratories. However, before the experiments were to start a certain amount of field data on wind, turbulence and temperature should be acquired at field sites in order to assist the laboratory investigators with establishing initial and boundary conditions for the model experiments.

REFERENCES

- Abe, M., 1941, "Mountain Clouds, Their Forms and Connected Air Currents," Part II. Bull. Centr. Met., Obs. of Japan, 7(3), 93-145.
- Armitt, J., and J. Counihan, 1968, "The Simulation of the Atmospheric Boundary Layer in a Wind Tunnel," Atmos. Environ., 2(1), 49-71.
- Batchelor, G. K., 1953, "The Conditions for Dynamic Similarity of Motions of a Frictionless Perfect-Gas Atmosphere," Q. Jour. R. Meteor. Society, 79, 225-235.
- Bernstein, A. B., 1965, "Dimensional Analysis Applied to the Wind Distribution in the Planetary Boundary Layer," Mon. Wea. Rev., 93(10), 579-585.
- Bogh, P., 1975, "Experience with Combined Wind Tunnel-Plume Model Analysis of Cooling-Tower Environmental Impact," Cooling Tower Environment-1974, CONF-740302, ERDA Symposium Series, 265-290.
- Carson, J. E., 1975, "Meteorological Consequences of Thermal Discharges from Nuclear Power Plants - Research Needs," Cooling Tower Environment-1974, CONF-740302, ERDA Symposium Series, 221-238.
- Cermak, J. E. and J. Peterka, 1966, "Simulation of Wind Fields over Point Arguello, California, by Wind-Tunnel Flow over a Topographic Model," Final Report, CER65-JEC-JAP64, Colorado State University.
- Cermak, J. E., 1971, "Laboratory Simulations of the Atmospheric Boundary Layer," AIAA Journal, 9(9), 1746-1754
- Chaudhry, F. H. and J. E. Cermak, 1971, "Wind Tunnel Modeling of Flow and Diffusion over an Urban Complex," Tech. Rep., CER70-71 FHC-JEC24, Fluid Dyn. Diffus. Lab., Colorado State University.
- Cook, N., 1973, "On Simulating the Lower Third of the Urban Adiabatic Boundary Layer in a Wind Tunnel," Atmos. Environ., 7, 691.
- Counihan, J., 1969, "An Improved Method of Simulating an Atmospheric Boundary Layer in a Wind Tunnel," Atmos. Environ., 3, 197.

- Counihan, J., 1973, "Simulation of an Adiabatic Urban Boundary Layer in a Wind Tunnel," Atmos. Environ., 7, 673.
- Fanaki, F. H., 1971, "A Simulation of Heat Flow in the Lower Troposphere by a Laboratory Model," Bound. Layer Meteor., 1, 345-367.
- Field, J. H. and R. Warden, 1929-30, "A Survey of Air Currents in the Bay of Gibraltar," Geophysical Memoirs No. 59 (Rand M 1563), Her Majesty's Stationary Office.
- Hunt, J.C.R. and H. Fernholz, 1975, "Wind-Tunnel Simulation of the Atmospheric Boundary Layer: A Report on Euromech 50," J. Fluid Mech., 70(3), 543-559.
- Lin, J. T. and G. J. Binder, 1967, "Simulation of Mountain Lee Waves in a Wind Tunnel," Tech. Rept., CER67-68JTL-GJB24, Fluid Dyn. Diffus. Lab., Colorado State University.
- Lloyd, A., 1966, "The generation of Shear Flow in a Wind Tunnel," Q. Jour. R. Meteor. Soc., 93, 79-96.
- McVehil, G. E., G. R. Ludwig and T. R. Sundaram, 1967, "On the Feasibility of Modeling Small Scale Atmospheric Motions," CAL Report No. ZB-2328-P-1, Cornell Aeronautical Laboratory.
- Murthy, C. R., 1970, "On the Mean Path of a Buoyant Chimney Plume in Non-Uniform Wind," J. of Appl. Meteor., 9, 603-611.
- Nee, V. W., A. A. Szewczyk and K. T. Yang, 1975, "Atmospheric Wind Tunnels - A Survey," ND-TR-WT-1, Dept. of Aerospace and Mechanical Engineering, University of Notre Dame.
- Nemoto, S., 1961a, "Similarity Between Natural Wind in the Atmosphere and Model Wind in a Wind Tunnel," Papers in Meteorology and Geophysics, 12(1), 30-52.
- Nemoto, S., 1961b, "Similarity Between Natural Wind in the Atmosphere and Model Wind in a Wind Tunnel (III)," Papers in Meteorology and Geophysics, 12(2), 129-154.
- Nemoto, S., 1962, "Similarity Between Natural Wind in the Atmosphere and Model Wind in a Wind Tunnel," Papers in Meteorology and Geophysics, 13(2), 171-195.
- Ogawa, Y., R. Griffiths and W. G. Hoydysh, 1975, "A Wind-Tunnel Study of Sea Breeze Effects," Boundary-Layer Meteor., 8, 141-161.

- Orgill, M. M., J. E. Cermak and L. O. Grant, 1971, "Laboratory Simulation and Field Estimates of Atmospheric Transport-Dispersion over Mountainous Terrain," Tech. Rept. CER70-71MMO-JEC-LOG40, Fluid Dyn. Diffus. Lab., Colorado State University.
- Orgill, M. M. and J. E. Cermak, 1972, "Atmospheric Flow and Diffusion Over Mountainous Terrain," AIAA Paper No. 72-648, AIAA 5th Fluid and Plasma Dynamics Conference, Boston, MA.
- Sethuraman, S. and J. E. Cermak, 1974, "Physical Modeling of Flow and Diffusion Over an Urban Heat Island," Advances in Geophysics, 18B, 223-240.
- Strom, G. H., 1966, "Simulation of Atmospheric Processes in a Wind Tunnel," On Atmospheric Simulation: A Colloquium, NCAR Tech. Note TN-22, 193-204.
- Sundaram, T. R., 1967, "On the Feasibility of Modeling Small Scale Atmospheric Motions," CAL Rept. ZB-2328-P-1, Cornell Aero. Lab., 19-111.
- Synder, W. H., 1972, "Similarity Criteria for the Application of Fluid Models to the Study of Air Pollution Meteorology," Bound. Layer Meteor., 3, 113-134.
- Synder, W. H., 1974, "Fluid Modeling Facilities for the Study of Air Pollution Meteorology," Draft Rpt., Meteorology Laboratory, Environmental Protection Agency.
- Willis, G. E. and J. W. Deardorff, 1975, "Laboratory Simulation of the Convective Planetary Boundary Layer," Atmos. Tech. No. 7(Fall), National Center for Atmospheric Research, 80-86.
- Yamada, T. and R. N. Meroney, 1974, "A Wind-Tunnel Facility for Simulating Mountain and Heated-Island Gravity Waves," Bound. Layer Meteor., 7, 65-80.

APPENDIX A

LOCATION OF LOW SPEED WIND
TUNNEL FACILITIES

LOCATION OF LOW SPEED WIND TUNNEL FACILITIES

United States

University of Michigan (2)
New York University
Colorado State University (4)
Calspan Corporation
Massachusetts Institute of Technology
Research Corporation of New England
Polytechnic Institute of New York
University of Houston
University of Notre Dame
University of Utah
Mt. Auburn Research Associates
Iowa State University
Illinois Institute of Technology
Purdue Aerospace Laboratory
California Institute of Technology (Guggenheim
Aeronautical Labs.)
Environmental Protection Agency (Meteorology Laboratory)
John Hopkins University
Oregon State University
U.S. Forest Service (Missoula, MT; Riverside, CA; and
Macon, GA)
University of Pittsburgh
Worcester Polytechnic Inst.
Kansas State University
Langley AFB, VA (NASA)
Tullahoma, Alabama (USAF)
Wright-Patterson AFB (NASA)
Boeing Corp. (Seattle)
Battelle, Pacific Northwest Laboratories (Richland)
University of Pennsylvania
Warren Spring Laboratory

Canada

National Research Council (2)
University of Western Ontario
University of Toronto (3)
McGill University

England

Bristol University
Watford (B.R.S.)
Leatherhead (C.E.G.B.)
Manchester
Edinburgh
Oxford
Salford
Southampton (Marchwood, C.E.G.B.)
Stevenage (Warren Spring Lab.)
Teddington (N.P.L.)
University of Leicester

France

Marseille (Institut de Mécanique Statistique de la
Turbulence)
Nantes (Centre Scientifique Technique du Bâtiment)
Ecole Centrale de Lyon
Poitiers
Toulon (Ecole Nationale Supérieure d'Electrotechnique,
d'Electronique et d'Hydraulique)
Chatou (Electricité de France)

Germany

Aachen
Bochum
Berlin
Hannover
Stuttgart

Netherlands

Amsterdam (N.L.R.)
Eindhoven

Austria

Vienna

Denmark

Lyngby (Hydro-og Aerodynamisk Laboratorium)

Norway

Trondheim

Sweden

Goteborg

Switzerland

Zurich (E.T.H.)

Italy

Mount Cimone Observatory

Japan

Nagasaki Technical Inst. (3)
Meteorological Res. Inst. (Japan Meteor. Agency), Tokyo (2)
Ochanomizu University, Tokyo
Kyoto University
National Research Inst. for Pollution and Resources, Tokyo (2)
University of Tokyo
Environmental Agency of Japan
Central Research Institute of Electric Power Industry,
Tokyo
Nihon University, Chiba (3)

Japan (Cont.)

Nippon Sheet Glass Company, Ltd., Chiba

Public Works Research Institute of Ministry of
Construction, Chiba (3)

Russia

Moscow University

USSR Central Institute of Labor Protection

Australia

Monash University

LIST OF SYMBOLS

<u>Symbol</u>	<u>Definition</u>
C	concentration of a diffusing material
C_p	specific heat at constant pressure
g	acceleration of gravity
K_R	reference coefficient of eddy viscosity
K_{ii}	coefficients of turbulent diffusivities for mass in x, y and z directions
K	coefficient for thermal diffusivity
k	von Karman constant
k_m	coefficient of molecular mass diffusivity
L	reference length
P	atmospheric pressure
Q_E	latent heat of evaporation and evapotranspiration
Q_G	transfer of heat through the ground
Q_H	turbulent transfer of sensible heat to the atmosphere
$Q_{L\uparrow}$	long-wave radiation emitted by the surface
$Q_{L\downarrow}$	long-wave radiation received by the surface from the atmosphere
Q_R	short-wave radiation reflected from the earth
Q_T	short-wave radiation from sun and sky
T	temperature
t	time
U_R	reference velocity
$\bar{u}$	mean wind speed

<u>Symbol</u>	<u>Definition</u>
u_i	velocity components in x, y and z directions
u_*	friction velocity
x, y, z	distances along longitudinal, lateral and vertical directions
ΔT_R	reference vertical temperature change
ν	coefficient of kinematic viscosity
ρ	air density
σ_{ij}	Reynolds stresses
$\bar{\sigma}_{ij}$	viscous stresses
$\bar{\Phi}$	energy dissipation function
Ω	angular rotation of the earth
δ_{ij}	Kronecker delta $\delta_{ij} = \begin{matrix} 1 & i=j \\ 0 & i \neq j \end{matrix}$
ϵ_{ijk}	permutation symbol
	$\epsilon_{123} = \epsilon_{231} = \epsilon_{312} = +1$
	$\epsilon_{321} = \epsilon_{213} = \epsilon_{132} = -1$
	all others = 0
κ	coefficient of molecular thermal diffusivity

Superscripts

- ' indicates fluctuation quantity
- indicates average quantity

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