[redacted]

USE OF WIND TUNNELS IN THE STUDY OF ATMOSPHERIC PHENOMENA

J. E. Cermak
Associate Professor of Civil Engineering
and Engineering Mechanics

and

Maurice L. Albertson
Director, Colorado State University Research Foundation

Colorado State University
Fort Collins, Colorado

Paper No. 58-32

Air Pollution Control Association

Annual Meeting
May 26-29, 1958 Philadelphia, Pennsylvania

CER58JEC18

USE OF WIND TUNNELS IN THE STUDY OF ATMOSPHERIC PHENOMENA

J. E. Cermak and Maurice L. Albertson

Colorado State University
Fort Collins, Colorado

Immediately upon the creation of a source for air pollution the region of contamination and the degree of contamination is almost entirely determined by the capricious whims of the local atmosphere. Accordingly, if one wishes to predict the possible contamination which might result from the creation of a particular type of source at a given site, an intimate knowledge of the local "winds" must be obtained. This knowledge must then be translated into some statement regarding the diffusive capacity of the local atmosphere. Despite the vast amount of field data collected to date and the theoretical accomplishments which have been made in fluid mechanics, each air pollution problem has complexities which seem to defy attempts of rational prediction.

Scale Modeling

One relatively undeveloped tool by which practical questions pertaining to the diffusion of contaminants from a given source and site may be answered in an economical manner is that of scale modeling. The success with which this tool has been applied to isolated problems of this character by Sherlock (7), Strom (8), Cermak (1), and Rouse (6) indicates that efforts should be made to extend the scope of wind tunnel modeling of atmospheric diffusion.

In the following paragraphs an attempt is made to state all the dominant variables affecting the diffusive capacity of the atmosphere. Certain dimensionless groupings of the variables are formed to provide model-prototype criteria or scale factors. Where it is possible, existing wind tunnel data or analysis are used to verify the importance of and the adequacy of certain techniques and scaling factors.

Factors Affecting Atmospheric Diffusion

Aside from molecular diffusion, atmospheric diffusion is determined primarily by the local scale and energy of the eddies or turbulence of the atmospheric surface layer. The latter mode (macroscopic mode) of diffusion is of the order of 10^3 to 10^5 times larger than the microscopic mode. Experimental evidence from both field and wind tunnel laboratory studies shows that the eddy diffusivity of the atmosphere depends upon:

1. The roughness and geometric characteristics of the earth's surface over which the approaching air has traveled.
2. The mean wind velocity.
3. The local geometry of the source site and the downwind geometry.
4. The density stratification caused by vertical temperature gradients.
5. Electrical and magnetic field intensities and their distribution.

In addition, the characteristics of the source contaminant -- density, initial velocity, particle size, and electrical charge--affects the resulting concentration at any instant of time.

The predominant perturbing factors affecting atmospheric diffusion can be classified as follows:

1. Dynamic
2. Thermal
3. Geometric

To arrive at scaling factors which will allow adequate extrapolation of model data of the concentration field to the prototype, variables describing the foregoing factors and the properties of the air and contaminant must be selected. By dimensional analysis the variables may be combined into dimensionless groups which constitute the scaling parameters.

The <u>dynamic</u> perturbation factors include the effects of mean velocity of the diffusive medium or some measure thereof, accelerations, and contaminant emission velocity. In most micrometeorological field studies, the mean velocity of the wind U at some predetermined level is used as a reference velocity. As shown in Ref. (1), a more definite measure of the effect of mean wind velocity and its vertical distribution upon the turbulence structure is the shear velocity $U* = \sqrt{\frac{\tau_0}{\rho_0}}$. This index is used in the following formulation of scale parameters. The phenomenon of forced convection is primarily affected by the factor $U*$. Accelerations which modify the flow pattern are the acceleration of gravity g and the Coriolis acceleration a_c. The contaminant emission velocity may be characterized by an emission velocity v_s if a single emission direction is considered—the initial turbulence of the contaminant being considered negligible.

<u>Thermal</u> influences on the diffusion field arise from creation of a lapse or inversion caused by the flow of air over a portion of the earth's surface which is warmer or cooler (usually caused by a net

gain or loss of thermal energy due to incoming or outgoing radiation) than the air. Such an influence may be characterized by the temperature difference ΔT of the air at two predetermined levels and the temperature T_1 at one of the levels. A second thermal influence is that caused by heating of the source contaminant; i.e., the cooling air from a nuclear power reactor or the gases from a coal burning power station. This effect may be represented by using a temperature difference ΔT_s or the emission gas density ρ_s may be used for a reference. Free or gravitational convection is especially sensitive to the thermal factors.

Variables describing the geometric perturbation factors are not well defined at the present time. The effect of upwind geometry, such as boundary roughness having the scale of trees, small structures, and large scale topographic features, is reflected in the scale ℓ and intensity I of the local turbulence and a length δ corresponding to the height to which the air flow is affected by the surface. Unfortunately, one cannot model upstream of the source as far as the air flow "remembers," accordingly means other than natural development of the flow over the scaled down geometry must be used in some cases to obtain a similar turbulence structure. Thus some reference ℓ and I appear to be a preferable index to the upstream geometry when δ is included as a measure for the scale of the bulk flow. Local geometry, such as the dimensions and distribution of structures, may be described by a sufficient number of length and angle variables. An extremely important geometric variable is a characteristic length term such as the source height H.

To complete the description of the diffusion problem, pertinent physical properties of the diffusion medium and the contaminant must be introduced. The significant physical properties of the atmosphere are the density ρ, the dynamic viscosity μ, the specific heat at constant pressure c_p, and the thermal conductivity k. A physical property of the contaminant which appears to be significant is the mean fall velocity V_f of any particulate matter emitted. If the contaminant is mixed with some uncontaminating material the contaminant emission concentration C_s must be added for a more complete description.

Dimensionless Groups Describing Diffusion Phenomenon

Several statistics of the concentration field may be used for representative measures. The one used in this discussion as a dependent variable will be the time mean concentration difference ΔC at a point. Gathering the variables introduced in the foregoing section, ΔC becomes a complex function generally expressible as:

$$C = \phi_1 (U^*, g, a_c, v_s, \ell, I, \delta, H, \text{geometry}, \Delta T, T_1, \rho, \mu, c_p, k, V_f, \rho_s, C_s, x, y, z) \qquad (1)$$

If the variables expressing C are grouped into dimensionless parameters by the use of a dimensional analysis, one of a variety of possibilities is the following formulation:

$$\frac{\Delta C}{C_s} = \phi_1 \left(\frac{U^*}{\sqrt{gH \, \Delta T/T_1}}, \frac{U^* H \rho}{\mu}, \frac{\Delta T}{T_1}, \frac{a_c}{g}, \frac{v_s}{U^*}, \frac{\ell}{H}, I, \frac{H}{\delta}, \frac{\mu c_p}{k} \frac{V_f}{U^*}, \frac{\rho_s}{\rho}, \frac{x}{H}, \frac{y}{H}, \frac{z}{H}, \text{geometry} \right) \qquad (2)$$

Thus, if similarity is to be obtained between the concentration field for a wind tunnel model and its atmospheric prototype, each of the parameters on the right hand side of Eq 2 must have the same value for both model and prototype. The Froude number $\frac{U^*}{\sqrt{gH\,\Delta T/T_1}}$ may be thought of as representing the ratio of inertia forces to forces caused by differences in specific weight. By the Reynolds number $\frac{U^*H\rho}{\mu}$ the ratio of inertia forces to forces due to viscosity is characterized. The perfect gas law can be used to transform the temperature ratio $\frac{\Delta T}{T_1}$ into $\frac{-\Delta\rho}{\rho_1}$. Thus, the temperature ratio expresses the effect of density stratification upon the inertia forces of the flow. Since one uses the same fluid--air--in both model and prototype, the gravitational acceleration g and the temperature ratio $\frac{\Delta T}{T_1}$ is the same in both cases, one cannot satisfy the Froude number $\frac{U^*}{\sqrt{gH\,\Delta T/T_1}}$ and the Reynolds number $\frac{U^*H\rho}{\mu}$ condition simultaneously; accordingly, one must be satisfied with a compromise to something less than exact similitude from the outset. Successful modeling of atmospheric phenomena such as diffusion rests upon the ability of the investigator to choose those parameters from Eq 2 which represent the significant features of the particular problem at hand.

Wind Tunnel Modeling of Atmospheric Diffusion

The usual wind tunnel for conducting atmospheric studies is a low velocity 5 to 100 ft/sec installation using the atmospheric medium of air as the test fluid at nearly atmospheric pressure. The test section cross-sections are usually rectangular with dimension on the order of 2 ft to 10 ft having lengths from 10 ft to 80* ft. Thus, model and prototype

---

* A 6 x 6 80 ft test section is currently under construction at Colorado State University.

velocities are essentially the same as those in the atmosphere and the scale length ratio is of the order of 1:500. Unless grids are introduced in operation of the test section, the intensity and scale of turbulence are of the order of 0.5 per cent and 0.1 in. respectively.

Examination of Eq 2 reveals the fact that only the parameters $\frac{U^*H\rho}{\mu}$, $\frac{U^*}{\sqrt{gH\,\Delta T/T_1}}$, $\frac{\Delta T}{T_1}$, $\frac{a_c}{g}$, $\frac{\ell}{H}$, I, and $\frac{H}{\delta}$ will need special consideration if a scale model is placed in the wind tunnel and a source devised to make the parameter $\frac{Vs}{U^*}$, $\frac{V_f}{U^*}$, and $\frac{\rho_a}{\rho}$ equal for model and prototype. In deciding between the criterion of the Froude number or the Reynolds number, particular attention must be given to the nature of the local geometry. If the local geometry is of sharp relief as it is for most structures, the viscous effects are relatively negligible so that Reynolds number may be disregarded and the Froude number becomes the significant parameter. On the other hand, if the local geometry and approach geometry is uninterrupted by structures or irregular topography the viscous effects may be so important that the Froude number may be insignificant by comparison with the Reynolds number and may be disregarded.

An illustration of the situation in which the Reynolds number is significant and the Froude number is relatively unimportant can be observed in the case of a model study of Lake Hefner (1) to determine evaporation rates and wind structure. Fig. 1 indicates that the evaporation coefficient is dominated by the Reynolds number for both the model and the prototype data. When the Reynolds number dominates the Froude number, it is obvious that similarity in the strict sense cannot be achieved because of the small scale ratio involved. In this case a general function can be established from the model data and then extrapolated to larger Reynolds numbers similar to the procedure exemplified by Fig. 1. Examination of Fig. 1 reveals the fact that the prototype data (for adiabatic conditions) are fairly well represented by the extrapolated curve.

The temperature ratio $\frac{\Delta T}{T_1}$ is important if the model investigation is to include the effects of diurnal atmospheric stability variations. Atmospheric stability has a profound influence upon the diffusive power of the atmosphere as is evidenced by the ribbon-like plumes (which diffuse horizontally only) during periods of inversion and the broad billowing plumes during periods of lapse. The most realistic way to achieve temperature ratio similarity is to heat and/or cool the model surface to create a thermal structure similar to that in the atmosphere. Studies by Cermak and Spengos (2) of boundary layer formation over a heated wind-tunnel floor 6 ft wide by 10 ft long indicate that mean velocity changes caused by the heating are similar to those caused by a lapse in the atmospheric surface layer. By referring to Figs. 2 and 3, the characteristic change in mean velocity profile curvature for lapse conditions in the atmospheric is seen to be present in the wind tunnel mean velocity profile taken at 9.3 ft downwind from the beginning of the heated plate. The wind tunnel temperature data of Fig. 4 indicate that a logarithmic vertical distribution exists which is similar to that for the lapse condition shown in Fig. 2 for the atmospheric surface layer.

Long (4) has discussed the relative importance of forces due to Coriolis acceleration a_c. For prototype dimensions up to the order of 10 km, the Coriolis acceleration exerts a minor influence on the state of flow. Because of scale limitations only wind tunnel models of prototype areas having dimensions less than 10 km appear feasible, hence the acceleration ratio $\frac{a_c}{g}$ appears to be relatively insignificant and can be dropped as a similarity requirement.

In studying the effect of turbulence intensity and scale upon evaporation from spheres placed in a wind tunnel, Maisel and Sherwood (5) found that the evaporation rate was very sensitive to turbulence intensity but not to scale. Thus, the parameter I should be retained as a similarity parameter. No definite information on the effect of $\frac{\ell}{H}$ upon the diffusion from a source such as a stack is available; therefore, the turbulence scale parameter should be retained also as a similarity parameter in such cases. The two parameters $\frac{\ell}{H}$ and I may be controlled in a wind tunnel to a considerable extent by placing grids of various mesh size at the upstream end of the test section and by varying the degree of boundary roughness on the upstream approach to the model proper.

The parameter $\frac{H}{\delta}$ has not been imposed as a similarity parameter in model studies to date. The chief reason for this is that existing wind tunnels have test sections too restricted in length to achieve realistic values of this ratio. Because of the necessity to have realistic values of $\frac{H}{\delta}$ in the model, the construction of a wind tunnel having an 80 ft long test section was initiated at Colorado State University. The atmospheric counterpart of the boundary layer thickness δ for the most part ranges between 100 and 1000 meters; therefore, for a 100 m high stack $\frac{H}{\delta}$ varies from 1 to 10. If a scale of 1:600 is chosen, the model stack height would be about 1/2 ft. Accordingly, with an 80 ft test section in which δ up to 2 ft can be attained, $\frac{H}{\delta}$ up to about 4 can be duplicated in the wind tunnel.

Concluding Remarks

Using known wind tunnel modeling techniques, the modeling of atmospheric diffusion phenomenon can be accomplished with a high degree of similarity. The primary similarity parameters can be expressed in the following forms:

Froude number	$\frac{U^*}{\sqrt{gH \quad \Delta T/T_1}}$
Reynolds number	$\frac{U^* \; H \; \rho}{\mu}$
Temperature ratio	$\frac{\Delta T}{T_1}$
Turbulence scale ratio	$\frac{l}{H}$
Turbulence intensity	I
Bulk flow scale ratio	$\frac{H}{\delta}$

Conflict in velocity requirements for a given scale ratio imposed by the Froude number and Reynolds number is a major difficulty only when the two numbers are of the same relative significance. In the modeling of diffusion in cities in which thermal effects are to be included, the Froude number dominates the Reynolds number and the lack of Reynolds number similarity becomes insignificant. When conditions are such that the two scaling parameters are of the same relative importance the possibility exists for modeling with Froude number similarity and then correcting for Reynolds number effects. When more knowledge about diffusion becomes available, the correction for Reynolds number effects may be made in a manner similar to that now used in ship modeling.

When the Reynolds number is more significant than the Froude number such as for flow over relatively flat terrain exact dynamic similarity cannot be obtained. However, by extrapolation of model data to larger Reynolds numbers which include the prototype range, behavior of the prototype can be predicted, see Fig. 1.

Because the wind tunnel offers a relatively inexpensive means for the study of atmosphere phenomena such as air pollution, municipalities and industrial organizations can profit greatly by making preconstruction model studies of potential air pollution problem areas.

References

1. Cermak, J. E. and Koloseus, H. J. Lake Hefner model studies of wind structure and evaporation - Part I and II. Report Nos. 54JEC20 and 54JEC22, Colorado State University, July 1954.

2. Cermak, J. E. and Spengos, A. C. Turbulent diffusion of momentum and heat from a smooth, plane boundary with zero pressure gradient. Final report - Part II Presentation of data and analysis, Colorado State University (Rept. No. AFCRC-TN-56-273) Dec. 1956

3. Halstead, M. H. Experimental verification of the equations for turbulent transfer. Seabrook, N. J. The John Hopkins University. Laboratory for Climatology, September 1951. (Contract No. W28-099-ac-378, Interim Rept. No. 15).

4. Long, R. R. Models of small-scale atmospheric phenomena involving density stratification in Fluid Models in Geophysics. U. S. Government Printing Office, Washington 25, D. C. 1953

5. Maisel, D. S. and Sherwood, T. K. Effect of air turbulence on rate of evaporation of water. Chemical Engineering Progress. Vol. 46, No. 4, 172-175. April, 1950

6. Rouse, H. Model techniques in meteorological research in Compendium of Meteorology AMS 1951 pp. 1249-54

7. Sherlock, R. H. and Stalker, E. A. A study of flow phenomena in the wake of smokestacks. Engr. Res. Bull. No. 29. Dept. of Engr. Univ. of Mich. March, 1941

8. Strom, G. H., Hackman, M. and Kaplin, E. J. Atmospheric dispersal of industrial stack gases determined by concentration measurements in scale model wind tunnel experiments. Paper No. 57-20. Air Pollution Control Assoc. Golden Jubilee Meeting, June 2-6, 1957

SYMBOLS

a_c	Coriolis acceleration
A	Area of evaporation surface
c_p	specific heat of air at constant pressure
C	mean of concentration at a point
C_s	contaminant concentration
ΔC	time mean of concentration difference $C_s - C$ at a point
E	average rate of evaporation per unit area
g	acceleration of gravity
H	source height
I	intensity of turbulence $\frac{\sqrt{(\overline{u^2} + \overline{v^2} + \overline{w^2})\ 1/3}}{U}$
k	thermal conductivity of air
ℓ	integral scale of turbulence $\int_0^r R_y dy$
R_y	two point velocity correlation coefficient
T_a	temperature of ambient air stream
T_1	temperature of air at elevation 1
T_s	temperature of source gases
ΔT	temperature difference between two levels $T_2 - T_1$
u	instantaneous fluctuation of x-component of velocity about the mean U
U	mean local air velocity
U_a	ambient velocity
U*	shear velocity $\sqrt{\frac{\tau_0}{\rho_0}}$
v	instantaneous fluctuation of x-component of velocity
v_f	mean fall velocity of contaminant particles
v_s	emission velocity of contaminant

w	instantaneous fluctuation of x-component of velocity
x	coordinate in direction of mean flow measured along a level surface
y	vertical coordinate
z	coordinate normal to mean flow
δ	boundary layer thickness
μ	dynamic viscosity of air
ν_e	coefficient of molecular diffusion for water vapor into air
ρ	mass density of air
ρ_o	mass density of air at surface
ρ_s	contaminant density
ρ_1	mass density of air at reference elevation
τ_o	surface shear stress