SCALE-MODEL WIND-TUNNEL STUDIES ON ATMOSPHERIC-DIFFUSION PHENOMENA

GORDON H. STROM
New York University

INTRODUCTION

During recent decades an increasing number of scale-model wind-tunnel investigations has been directed to problems of atmospheric diffusion. The great majority has dealt with specific applications, usually in the field of air pollution. Although the investigations generally lack the approach directed to the fundamentals of diffusion phenomena and necessary modeling techniques, the need for accurate results has often led to important developments.

Most past wind-tunnel investigations on air pollution have concerned large industrial plants, often steam power plants. Results of such investigations are used in making decisions involving plant design or modification of considerable economic significance. With this status of model studies, one might expect to find a considerable amount of verification data on accuracy of model experiments, but such is not the case. On the contrary, there is a lack of such data. The situation is, fortunately, not as dark as it may seem. There is a background of experience which shows satisfactory results without yielding specific confirmatory data.

Most scale-model diffusion studies have dealt with cases dominated by air motions originating at large physical obstructions. Air turbulence and patterns of mean motion produced by buildings, topographical features and other objects were the important features. Thermal and air-viscosity effects were of secondary importance. Success has been due at least in part to this simplicity.

Past studies also often have been of the semi-quantitative type insofar as diffusion characteristics are concerned. Only geometric features of gas plumes were determined. These may be sufficient for some purposes; for others they may be used in conjunction with gas-diffusion theories to obtain estimates of concentration characteristics. Improvements in gas concentration instruments have made feasible measurements of gas-concentrations directly in model experiments similar in form to those obtained in full-scale studies. With increased knowledge on tolerance levels for various atmospheric pollutants concentration measurements are becoming more valuable.
Scale-model diffusion experiments on gaseous effluents from stacks involve control of source characteristics as well as of atmospheric variables. The major influence of source characteristics is on the path of a gas plume although the jet action induces turbulence which affects diffusion. The two significant source variables in addition to geometry are gas ejection speed and density or their equivalents in terms of other variables. Control of density is a more recent development and is sometimes omitted because of the added experimental complications and its lesser importance under some conditions such as high wind speed.

The size of modeled regions has been on the order of a few miles downwind of the source. Some increase may be expected but will be limited by larger-scale thermally-induced motions which have not as yet been modeled. The larger scale motions will not be considered in this paper.

Scale Factors and Modeling Problems

Modeling of simple diffusion sources, i.e., cases in which the source does not affect the diffusion pattern, are primarily problems of modeling atmospheric motions. Owing to the number of variables involved, modeling of atmospheric motions can lead to so many scale factors as to make the problem extremely difficult if not impossible to manage. In common with other fields of modeling, a selection must be made as to which variables are significant to a particular case, or, more realistically, it must be determined which types of atmospheric motions are capable of being modeled. In cases of complex source characteristics, the modeling problem is further complicated with additional scale factors resulting from source variables. An extensive list of source and atmospheric variables is given in [1].

The various scale factors discussed here will be presented on the basis of a dimensional analysis with the selected variables. Some atmospheric variables for which modeling techniques are not as yet fully established are included along with those common to successful investigations. There are some obvious omissions of physical variables which will be discussed later.

The concentration $\chi$ in a gas plume is assumed to be

$$\chi = f[x, h_s, h_b, Q, \rho_s, V_s, u, u_0, \rho, \Delta (d\rho/dz), g, \delta]$$

(1)

in which the variables are defined as follows:

$\chi$ gas concentration at a given location downwind of the source, mass per unit volume

$x$ distance downwind of source

$h_s$ height of stack above ground

$h_b$ height of building

$Q$ source emission rate, mass per unit time

$\rho_s$ mass density of effluent
The variables are shown schematically in Fig. 1. $x$ denotes downwind distance at which concentration $\chi$ is taken, generally at ground level. For specific crosswind locations and other elevations, additional coordinates could be introduced but they would only confirm the requirement for geometric similarity which will appear in the dimensional analysis. Additional dimensions will obviously give a more complete specification of configuration including position relative to wind direction but will not introduce new features in the results.

$Q$, $\rho_s$, and $V_s$ are stack effluent variables determined by the source. $u$, $u_0$, $\rho$ and $\Delta(d\rho/dz)$ are atmospheric variables; $\Delta(d\rho/dz)$ and $u$ (variable with elevation) have generally not been controlled in scale model experiments but must be introduced in any advanced developments of the future.

The following equation may be formed by dimensional analysis. The dimensionless concentration ratio $\chi u \delta^2/Q$ is here taken as a function of the remaining dimensionless groups:

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\[ The \text{ following equation may be formed by dimensional analysis. The dimensionless concentration ratio } \chi u \delta^2/Q \text{ is here taken as a function of the remaining dimensionless groups:} \]
The various dimensionless groups must be maintained at the same value in the model as in the atmospheric prototype for proper modeling of the various physical phenomena. They may be used to form various scaling equations which relate model-test variables to their full-scale counterparts.

The first three dimensionless groups \( \frac{\chi u_0^2}{Q} \), \( \frac{x}{\delta} \), \( \frac{h_s}{\delta} \), \( \frac{h_b}{\delta} \), and other similar ratios which could be formed from additional dimensions require geometry to be preserved between model and prototype. This includes wind direction, as well as configuration of structures, surface features, etc. Although any linear dimension could be used as the common reference, boundary-layer height \( \delta \) is here used to emphasize the atmospheric characteristics, even though geometric similarity of boundary-layer height has not been maintained in past scale model experiments. In the usual application having no control of boundary layer, \( \delta \) may be taken as an arbitrary reference dimension having a fixed ratio to a reference dimension of the rigid model such as stack height in a stack-gas diffusion problem.

The fourth, fifth and ninth groups on the right side of Eq. (2) deal with characteristics of the source. These cover the usual case of stack gas with density different from the ambient atmosphere. \( \frac{Q/\rho_s V_s \delta^2}{\rho_s V_s \delta^2} \) is unnecessary if the requirements of geometric similarity include stack-exit cross section since \( \delta^2 \) will then be proportional to exit area.

In some experiments \( \rho_s/\rho \) and \( V_s/u \) have been combined to form \( \rho_s V_s^2/\rho u^2 \). This group may be interpreted as the ratio of momenta changes in the emitting gas and ambient airstream and appears to be a suitable requirement for similarity in shape of gas plume near the source. For greater downwind distances the effects of upward velocity \( V_s \) and plume density \( \rho_s \) cannot be so combined, if there is appreciable density effect.

The three dimensionless groups \( \frac{u_0^2}{g \delta} \), \( \frac{u}{u_0} \), and \( \frac{\delta \Delta (dp/dz)}{\rho} \) concern atmospheric variables. The Froude number \( \frac{u_0^2}{g \delta} \), which arises because of gravitational action on fluid elements of differing density, determines the reference speed at which the experiment must be conducted. Since this speed must be proportional to the square root of linear scale, model-test speeds become extremely low. They are generally below 5 fps for model scales normally encountered, and lead to much difficulty in wind tunnel design and operation because of the occurrence of undesired convective air motions.

Another form of Froude number is used in some fluid model experiments where gravity plays a part. It includes fluid density characteristics and allows selection of speed by change in density. Use of this form of Froude number does not seem to have been investigated for gas diffusion.
experiments. It does not offer much advantage for stack-gas experiments since gas densities are already so low that additional reduction is difficult to achieve. Furthermore, this form of Froude number does not satisfy the momentum relationship which appears significant near the stack exit.

\[ \frac{u}{u_0} \text{ and } \delta A \frac{(d\rho/dz)}{\rho} \text{ determine the vertical profiles of air velocity and density. Control of these characteristics in a scale model introduces features which distinguish meteorological wind-tunnel modeling from other types of aerodynamic experiments. The significance and effective application of these particular forms of scale factors remains to be established, but they are at least a starting point for an important aspect of atmospheric modeling. To suggest that a velocity profile be adjusted to fit selected profiles of the atmosphere in accordance with the requirement } u/u_0 \text{ may seem absurd in view of the well established velocity profiles for flat plates which follow other relationships. Rough surfaces may, however, on further exploration yield the kind of control needed. There is a suggestion of this form of action in some published results for rough surfaces when viewed in light of the logarithmic equation for fully turbulent flow over rough surfaces (see for example Eq. 3.44 of [2])

\[ \frac{u}{u_*} = \frac{1}{k} \ln \left( \frac{z}{z_0} \right) \]  

(3)
in which \( k \) is the Kármán constant, \( z_0 \) is roughness length and \( u_* \) the friction velocity which is related to surface shear stress \( \tau_0 \) by

\[ u_* = \sqrt{\frac{\tau_0}{\rho}} \]

In terms of the free stream velocity \( u_0 \)

\[ \tau_0 = C_f u_0^2/2 \]

From the above equations

\[ u_* = \sqrt{\frac{C_f}{2}} u_0 \]

and on substitution into Eq. (3)

\[ \frac{u}{u_0} = \left( \sqrt{\frac{C_f}{2}}/k \right) \ln \frac{z}{z_0} \]  

(4)

When experimental results on shear stress presented in [3] (Figs. 1 and 4 of Chapter V) are replotted, the following equation gives a satisfactory fit:

\[ C_f = B \left[ \ln \left( \frac{1}{\epsilon} \right) \right]^2 \]  

(5)

where \( B \) is a constant, \( l \) the length of plate or body, and \( \epsilon \) the grain size of surface roughness. In Eq. (4) \( z_0 \) is approximately proportional to grain size

\[ z_0 = b \epsilon \]  

(6)

where \( b \) is a constant.

Equations (4), (5) and (6) may be combined to form

\[ \frac{u}{u_0} = D \ln \left( \frac{z}{b \epsilon} \right) / \ln \left( \frac{1}{\epsilon} \right) \]

(7)
in which \( D \) is a constant. \( l \) has no counterpart in the atmosphere, but an interesting result is obtained, if \( l \) is assumed to be a measure of linear
scale. This is not an unreasonable assumption. Consider Eq. (7) in its application to model and prototype. If the grain size is scaled in proportion to linear scale (which will preserve geometric similarity), $1/\epsilon$ will be the same for model and prototype. For geometrically similar elevations, $z/b\epsilon$ is also the same for model and prototype. The result is equal values of $u/u_0$ which is in accordance with the above scale factor on velocity profile.

The velocity-profile scale factor $u/u_0$ has other significance quite apart from its relation to shear stress and surface roughness. This concerns the effect of local wind speed on plume characteristics. The ground-level and other fixed-location concentration will be markedly affected by local wind speed at the source and along the path of the gas plume since it will affect the height of plume. Another effect is the diluting action of local wind speed which is included in the concentration scale factor $xu\delta^2/Q$.

The scale factor $\delta\Delta (d\rho/dz)/\rho$ containing the vertical density gradient may be expressed in terms of a temperature gradient $dT/dz$ ($T$ is absolute temperature) and an adiabatic gradient $-\Gamma$ as

$$-\delta (dT/dz + \Gamma)/T$$

or in terms of potential temperature $\Theta$ as

$$-\delta (d\Theta/dz)/\Theta$$

This scale factor is a measure of static stability and is significant for its relation to convective turbulence. It requires the model temperature to be increased as scale is decreased.

The Richardson number frequently appears in discussions of atmospheric turbulence [2],

$$R_i = g(dT/dz + \Gamma)/T(u_0/\delta)^2$$

A group similar to the Richardson number results from the ratio of the Froude number to the density-gradient scale factor as follows:

$$g(dT/dz + \Gamma)/T(u_0/\delta)^2$$

For similar velocity profiles, $u_0/\delta$ is proportional to $du/dz$ and the two groups are alike. It remains to be established whether the Richardson number is a satisfactory replacement for the Froude number and the density-gradient scale factor in scale-model experiments.

In looking over the dimensionless groups in Eq. (2), the obvious omission of a Reynolds number $u_0\delta\rho/\mu$ is noted which would have appeared if the air viscosity $\mu$ had been included in the group of variables of Eq. (1). Viscosity is omitted because of practical difficulties in modeling atmospheric diffusion. Simple diffusion problems in which there are no density effects could be conducted in accordance with Reynolds number similarity but the introduction of density characteristics leads to a Froude number which is in conflict. Cases with density effects cover such a wide range of atmospheric conditions and source characteristics that the applicability of scale
model experiments would be severely restricted if omitted. There are, however, many cases in which viscosity has negligible effect. Included are those in which turbulence important to diffusion is caused by angular objects and obstructions. An outstanding example of negligible viscous effect is the wind tunnel investigation [4] on a 1/5,000 scale model of the Rock of Gibraltar where good agreement between model and prototype was found for flow patterns and regions of turbulence. Boundary layers over plane surfaces with considerable roughness show little effect of viscosity except at extremely low values of Reynolds number. Flow over smooth surfaces has the well known dependence on Reynolds number and is not likely to be successfully modeled where phenomena requiring Froude number similarity are involved.

Omitted from above considerations is the transport of particulate matter through the atmosphere. Sufficiently small particles will have the same motions as the ambient air but larger sizes will show an effect of particle fall velocity. Very little seems to have been done with this type of modeling. New scale factors will have to be developed and these will encounter complications from the dependence of fall velocity on Reynolds number.

Industrial Air-Pollution Problems

The great majority of scale-model wind-tunnel studies on air-pollution problems have dealt with large industrial plants having considerable volume of stack effluent. These studies have several features in common, features which have undoubtedly played an important part in their success. Stack effluent is discharged upward in the conventional manner from one or a group of stacks and it has a density lower than the ambient atmosphere. There is generally one or more buildings of considerable size at or near the stack. Significant topographical features along with other obstructions to air motion are sometimes present.

An important feature of the successfully modeled industrial problem is the occurrence of critical pollution conditions (high ground-level concentrations) at high wind speeds. Upward momentum and buoyancy of a gas plume tends to keep it clear of the ground at low wind speeds. With increasing speed the plume is deflected toward the ground. After the plume first contacts the ground, concentration increases with wind speed until the diluting effect of higher speeds dominates. The meteorological importance of high wind speed is the high level of mechanical turbulence which tends to minimize thermal effects and makes the modeling problem simpler. At speeds above 15 mph depending on ground-surface and thermal conditions, mechanical turbulence is so strong that convective turbulence caused by thermal influence is negligible in comparison. Wind speeds at which serious
ground-level pollution occurs are usually in this range of predominantly mechanical turbulence.

Another simplifying factor in these industrial air-pollution problems is the strong influence on plume motions of air turbulence and flow pattern resulting from buildings and other obstructions. Except for determination of wind speed at plume level, the influence of the boundary layer formed over upwind regions is minimized. Conventional wind tunnels which feature a uniform airstream may, therefore, be used even though they have no control of boundary layer profiles or means of producing convective turbulence. The success of many scale-model studies in such wind tunnels is evidence of this fact.

The lack of confirmatory prototype data may seem incongruous in view of the economic importance of uses made of model results. There have been various prototype field studies made at plants for which scale model investigations were conducted. Usually these have been conducted before the wind tunnel project and lacked measurements necessary for meaningful correlation studies. Unfortunately, the scope of required field measurements is beyond that needed for most pollution evaluations and is likely to be quite costly. The time element is such that a field study started when wind-tunnel studies are first planned is not likely to yield the required data in time to evaluate model results before their application. The tendency is to await results of prototype operation.

There is a body of experience with scale-model applications which appears to give an acceptable evaluation in lieu of specific correlation studies. It is not uncommon to learn that a plant modification or new plant operation proved to be satisfactory as measured by lack of complaints or other common evidence of satisfactory pollution characteristics. Such cases taken as isolated incidences are not significant but as an accumulation of experience over a period of years they inspire a fair degree of confidence.

Correlation Studies on Steam Power Plants

The following two scale-model studies conducted in the New York University wind tunnel show satisfactory agreement with the prototype in some situations and lack of agreement in others. They emphasize some modeling problems and point out the need for closer measurement and control of test variables.

The first case [5] concerns the Avon Lake Plant of the Cleveland Electric Illuminating Company. The Cleveland Company conducted various prototype studies prior to the scale-model project. These included measurement of sulfur dioxide concentration along with wind speed and direction. There were two interesting results of the correlation studies. One showed the need to operate the model stacks at the correct gas density,
the other the satisfactory agreement with prototype measurements obtained within the limitation of test measurements.

The wind-tunnel project was started without control of stack-gas density, as was the procedure for prior projects in this wind tunnel. Since omission of stack-gas density control eliminates the Froude number as one of the scale factors, selection of model wind speed is left open. It had been found that a speed of 8 mph was a good working value for this tunnel as the airstream was uniform and the demands on the smoke generator were reasonable. With omission of stack-gas density control, the remaining requirement on stack operation is the stack-gas ejection speed to wind-speed ratio $V_s/u$.

There remains the problem of lack of agreement between model experiment conducted with density at ambient conditions and the prototype where the density is considerably lower than ambient air. It is impossible to obtain general agreement by adjustment of gas-ejection speed but an improvement in plume path close to the stack may result if the ratio of momentum changes for gas to airstream $\rho_s V_s^2/\rho u^2$ is maintained the same for model and prototype. With this modification, model ejection speed $V_s$ will be less than required by the speed ratio $V_s/u$. Whether this procedure is justified in the general case is open to question since there is no correction for plume rise due to density. It may be better to maintain $V_s/u$ so as to include an excess of momentum rise as a partial substitute for density rise. With test results for a range of velocity ratios the various possible procedures may later be analyzed in the light of their application.

The only available test results common to model and prototype and useful for correlation purposes was the wind speed at which the plume first contacted the ground. Initial tests showed lack of agreement. For the most critical wind direction, the speed of initial contact for the model (converted to full scale) was 10 mph and for the prototype close to 20 mph. It was well known that lack of stack-gas density control was conservative but in this case the result was considered too conservative for practical application.

Detection of the wind speed at which initial contact occurred was based on photographic and visual observations. This was later improved with the introduction of a detector consisting of a spotlight which projected a light beam on a phototube across the airstream close to the surface. Diminution of phototube output, caused by interruption of the light beam by smoke from the model stacks, was used to detect the presence of the plume at ground level. Determination of initial contact speed was facilitated by plotting change in phototube output against wind speed. The phototube measurement is approximately proportional to smoke concentration (actually line concentration) and is a valid method of determining initial-
contact speed for correlation with that obtained from sulfur dioxide measurements in the prototype. Results for the Avon Lake Model with no control of gas density are shown in Fig. 2. These confirmed the initial-contact speed of 10 mph determined earlier in the visual experiments. Field results for the prototype are also shown and the lack of agreement is obvious. Only the initial-contact speed (first speed of measurable concentration) is significant in this graph since there was no concentration calibration of the wind-tunnel smoke detector. The slope of the relative-concentration curve is arbitrary. Figure 2 is based on Fig. 6 of [5], but additional data are included.

Control of stack-gas density in the next series of tests was accomplished in such proportions as to give the same density as that of hot gases in the prototype stacks. With this additional variable, wind speed must be set in accordance with the Froude number. For the scale of 1/240, a prototype wind speed of 20 mph required a model test speed of 1.2 fps. At this speed, the wind tunnel did not produce satisfactory flow in the test section. Various tunnel modifications were made to improve the flow, and model tests were conducted with stack-gas density at the proper value. The results

![Figure 2: Relative Ground-Level Concentrations of Stack-Gas and Smoke Plumes for Prototype and Wind-Tunnel Model—Avon Lake Steam Power Plant at Critical Wind Direction.](image-url)
are shown in Fig. 2. The agreement with prototype was considered satisfactory.

The second correlation study concerns another steam power plant. Prototype data was in a form different from that of Avon Lake in that four specific cases of complete plant operating data along with wind speed and direction were selected by the project sponsor from results obtained over a period of time. In these cases conditions were constant long enough to obtain well defined results. They occurred at different wind directions but within a 45° range. The various stacks were operating at different loads. These were reproduced in the model. Model scale was 1/300. Sulfur dioxide concentration measurements were made at ground level downwind of the model.

An important result of this study which was not realized at the time the experiments were conducted was the importance of the velocity profile in the vicinity of the plant where the prototype anemometer was located. Velocity profiles measured at the model showed that the anemometer level was well within the boundary layer caused by upwind obstructions. Model airspeed was measured at a higher level in the free stream above the bound-

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**Fig. 3. Ground-Level Sulfur Dioxide Concentrations for Steam Power Plant and Wind-Tunnel Model—Vertical Line Segments Show Range of Prototype Values.**
ary layer. Model velocity profiles showed the speed at anemometer level to be approximately 60 per cent of free stream. The need for correct speed is evident from the sensitivity of the concentration curves in Fig. 3 to small changes in wind speed in the range of increasing concentration.

Scale-model and prototype results are plotted in Fig. 3. Wind-tunnel measurements were taken over a 10-mph range to bracket the nominal prototype wind speed for each of the four cases. With these unadjusted wind speeds, there is no agreement for cases 1 and 3 but cases 2 and 4 are reasonably good. Analysis of the disagreement in cases 1 and 3 suggested a large inaccuracy in an important test variable. The wind-speed profile gave at least a partial solution. There were no prototype velocity profiles available; therefore, adjusted wind speeds for prototype concentrations were calculated on the basis of the 60-per-cent free-stream value found at the anemometer level in the wind-tunnel experiments. They are shown in Fig. 3.

Adjusted prototype speeds, unfortunately, are at the upper end of the speed range for model concentration data in cases 1 and 3 and well beyond in cases 2 and 4. The extrapolation of model curves in Fig. 3 for cases 2 and 4 are based on prior experience with models of this type. Case 2 prototype is lower than the model experiment and case 4 higher. Case 3 shows fairly good agreement but case 1 is still in disagreement although a little better than the unadjusted case. Case 1 remains unresolved but is receiving further study. Its wind direction was 30° from the nearest of 2, 3 and 4. These three occurred in a 15° range.

In judging the degree of correlation between model and prototype for the two model studies presented above as well as others of a similar type, consideration must be given to the number of test variables involved and the problem of obtaining accurate measurements. Both stack and atmospheric variables have first-order effects. It is often difficult to obtain simultaneous measurements of all variables. Inaccuracy in only one may make a large difference in gas-concentration results. Prototype wind measurements may be affected by local influences not readily detected. The wind-tunnel experiments are conducted at extremely low speeds at which accurate measurements are difficult to obtain. Gas concentrations are very low and subject to many extraneous effects.

**Diffusion Experiments with Convective Turbulence**

The following comparison of two wind-tunnel diffusion experiments with field studies show good agreement for the limited range of conditions covered, to the extent that the two may be compared. Both deal with a point source of sulfur dioxide near the ground. The wind-tunnel experiments were conducted in the New York University wind tunnel for neutral and unstable thermal conditions. The field studies were conducted under
Project Prairie Grass during the summer of 1956 under sponsorship of the Geophysics Research Directorate, Air Force Cambridge Research Center [6]. A large number of diffusion experiments were conducted over a wide range of thermal stability conditions.

In the wind-tunnel experiments, see Fig. 4, a sulfur dioxide source was located 0.3 inch above the floor and approximately 30 feet from the test section entrance. Upstream from the source, the floor was covered with laterally placed roughness strips \( \frac{3}{8} \) inch high at approximately one-foot spacing. The strips were introduced to increase boundary-layer height and induce turbulent flow at the gas plume. Sulfur dioxide concentration was measured with a Consolidated Electrodynamics Titrilog. Samples were drawn from selected downwind and crosswind locations one-half inch above the surface. Only one location could be sampled at one time and each was run about five minutes.
Reference wind speed $u_0$ was measured in the free stream well above the boundary layer. Limited velocity-profile measurements served to determine wind speed at source level, but they were not suited for evaluating other characteristics. For a free stream speed of 1 fps the source-level air speeds were 0.30 and 0.37 fps for neutral and unstable conditions, respectively. At a free stream speed of 2 fps, source-level speed was 0.74 fps for neutral conditions. Floor-surface temperature control was used for neutral as well as unstable operation. In the neutral condition, temperature was constant with height within 0.05°F. A temperature gradient of $-0.28°F$ per foot (temperature decreasing with height) was obtained in the unstable case.

Crosswind profiles of gas concentration 65.6 inches downstream from the source are shown in Fig. 5. Although the number of test readings is limited and shows scatter, typical distribution of a gas plume is evident. Since the points for each profile were obtained over a period of one hour or more, scatter may be due in part to drift in test conditions.
Comparison of wind-tunnel and field experiments is presented in Fig. 6, with the wind-tunnel results converted to full scale in accordance with the scale factors presented earlier. These experiments lack geometrical characteristics which could be used to determine a linear scale. For the purpose of this study, therefore, a linear scale of 1/240 is assumed. This is typical of scale model air pollution projects conducted in this wind tunnel. Fortunately, the comparison in Fig. 6 is not sensitive to scale. Similar results would be obtained with considerable change in the assumed linear scale. Concentration values are expressed in terms of the parameter \( \chi \nu u / Q \) to eliminate effect of source strength and wind speed. \( u \) is the wind speed at the source and \( \chi \nu \) the maximum concentration at a given downwind distance. In accordance with the concentration scale factor \( \chi \nu u^3 / Q \), wind tunnel values were multiplied by \((1/240)^2\), the square of linear scale, to convert them to full scale equivalents and are so plotted in Fig. 6.

Regions of stability and instability for the field experiments shown in Fig. 12 of [6] are delineated in Fig. 6. The reference figure shows a family
of curves of constant standard deviation of azimuth wind direction. The stable region occurs at nighttime and unstable daytime with neutral bordering on the two. Boundaries of stability regions shown in Fig. 6 are along lines of constant standard deviation of azimuth wind direction and are, effectively, lines of constant turbulence conditions.

Numerical values of standard deviation are not shown in Fig. 6, since there were no corresponding measurements in the wind tunnel experiments. Comparison of stability characteristics must, therefore, remain qualitative but the magnitude of temperature gradient in the model aids the interpretation of results. For this purpose, the scale factor on temperature gradient \( \delta \left( \frac{dT}{dz} + r \right) / T \) is useful. No numerical values for absolute temperature \( T \) were given, but they are not expected to differ enough to affect the results and will be assumed to have the same value. For the case of neutral stability, the temperature gradient has the adiabatic value \(-T\) and the scale factor, consequently, is zero. Numerically, \( dT/dz \) is then \(-0.0055^\circ \text{F per foot}\). Temperature measurement in the tunnel is not accurate enough to detect the difference between isothermal and adiabatic gradients for the height of airstream available. From a practical viewpoint, the adiabatic gradient will appear isothermal.

In the unstable case, as mentioned, the temperature gradient found in the wind tunnel was \(-0.28^\circ \text{F per foot}\). When converted to full scale with the temperature-gradient scale factor using 1/240 linear scale, \( (dT/dz) + r \) becomes \(-0.0012^\circ \text{F per foot}\) or \( dT/dz \) equals \(-0.0076^\circ \text{F per foot}\).

Qualitative agreement between wind tunnel and field experiments is evident from Fig. 6 for both neutral and unstable cases. In the unstable wind-tunnel experiment, the temperature gradient relative to the adiabatic \( (dT/dz) + r \) has a value of \(-0.0012 \) which is approximately one-fifth of the adiabatic gradient. In extremely unstable conditions temperature gradients in the lower layers of the atmosphere may reach values several times the adiabatic value. Thus the experiment has rather weak instability. The results agree with this interpretation.

Decrease of peak concentration with distance is less than that of the field studies. There are many factors which could cause this difference, but there is not enough information to evaluate their importance. Since viscous forces are not scaled in the model experiment, their effects may be more evident and more so in this type of experiment since the diffusion starts in the lowest portion of the boundary layer. There are configurational differences between model and full scale which may affect the results. Scaled height of source and sampling points were higher than full scale. Upstream surface roughness was different in that the surface was very smooth for the field experiments while there were roughness strips in the
model. Since there is no comparison of velocity profiles, significant differences in boundary layer characteristics could exist.

Gas sampling period is a factor of importance in concentration measurements. As sampling period is reduced, maximum concentration tends to increase since the diffusive effects of long period and large amplitude turbulent fluctuations is reduced. The effect of the sampling period is, therefore, dependent on the spectral properties of turbulence. The longer-period fluctuations of the atmosphere are not modeled within the confines of the wind-tunnel test section. Thus a sampling period beyond a certain value may, in the model, lose the significance it has for the corresponding periods of the atmosphere. The scale factor on time can readily be shown as the square root of linear scale. The sampling period used in the field experiments was 10 minutes. The corresponding scaled period of 39 seconds in the model is probably longer than the turbulent fluctuations. If there is any effect of differences in sampling period, it probably raises the wind-tunnel concentrations relative to full scale.

Conclusions

Scale-model wind-tunnel experiments on gas diffusion show satisfactory agreement with their full-scale counterparts when the diffusive action is dominated by mechanical turbulence which originates at angular and blunt obstructions to air motion. These include cases where buildings or significant topographical features are the main elements. There must be no thermal influences which cause convective air motions; high speeds tend to satisfy this condition.

The influence of the momentum and density of stack gases on ground-level concentration can be reproduced in the model.

Diffusion by convective air motions due to thermal characteristics of the surface and the atmosphere shows promise of effective modeling but much research remains to be done before its possibilities can be established.

Additional correlation studies are needed to place diffusion modeling of all levels of complexity on a firmer basis. Limitations and capabilities must be clearly established.

There is need for instruments which on a routine basis without frequent recalibration can accurately measure low air speeds, small differences in temperature, and low concentrations of gases suitable for diffusion experiments.

REFERENCES


**Discussion**

Alan Faller remarked that geostrophic flow, which is the essential feature of atmospheric circulation, could be obtained by making the Reynolds number high enough so that viscous effects would be small relative to inertial effects. However, viscosity enters in important ways, particularly in the rate of dissipation of kinetic energy in the atmospheric model. He said that the time scale for dissipation of kinetic energy in his model was such that the time for energy dissipation should have been about two weeks. In the model, even though geostrophic flows were closely approximated, the time for energy dissipation was close to one day or one revolution. It seems that the rate of dissipation of kinetic energy would be important in the study of flow around obstacles even though the Reynolds number is high in both cases. As flow proceeds downstream from the source of turbulence the diffusion of material would be appreciably less in the model than in the prototype just because the eddies dissipate at a more rapid rate in the model. The speaker replied that certainly the decay of turbulence would be more rapid but more energy is being supplied to the system. The inquirer asked if the source of energy was not the turbulence around the buildings and if the flow did not become laminar downstream. The speaker agreed that if the stream were comparatively free from such boundary influences this would be true. The smoke stream is introduced well up in the test section and away from the walls so the initial diffusion is due to turbulence created by the probe and whatever is associated with it. From then on the stream remains substantially constant and a pocket of smoke can be followed for a considerable distance. At the boundary, however, there is a marked influence and much additional study would be required in cases of smoother surfaces without large obstructions which dominate the flow.

Captain Wright remarked that the David Taylor Model Basin, after running experiments on ship-stack gases in wind tunnels for many years, has now begun to perform such experiments in water. The superstructure of the ship is modeled, attached to a board, and tested inverted in the circulating water channel. A dye mixed with water is then injected at the desired ratio of stack gas to approach velocity. It is relatively easy to
obtain super-critical Reynolds numbers under such conditions and the motion is very majestic; so it is easy to follow visually. Also, rather good full scale correlation has been obtained with this technique. The fluid is emitted from the stack but the density is not controlled. It is found that for the length of the flight deck of an aircraft carrier or the bridge structure of a ship the density is not a controlling factor. The speaker pointed out that at higher wind speeds density is of less significance.

Rex Elder stated that in a model study with a scale of 1:540 the topography upstream from the plant was reproduced for a distance of about 7500 feet. The correlation between wind-velocity profiles in nature and in the model was remarkably good for high wind velocity at nearly neutral conditions. The correlation between the model and the prototype was relatively good for sulfur-dioxide concentration also.

Maurice Albertson remarked that the diffusion of a smoke plume depends on two sources of circulation or turbulence. One is the free stream approaching from upstream and the other is turbulence associated with the structures in the immediate vicinity. It is important to have the turbulence and velocity profiles created by an upstream boundary in the model the same as that in the prototype; in other words, the boundary shear must create the velocity profiles, the associated turbulence profiles, and the spectrum of the turbulence, at each point above the boundary. Therefore, there must be enough distance upstream to create a boundary layer sufficiently thick for the structure to be inside of it. Under these conditions the turbulence downstream from the structure and the behavior of the smoke plume will be more nearly like that found in the prototype. In connection with the Reynolds-number effect careful consideration should be given to the fact that there are boundary influences in the model which may cause the viscosity to enter rather predominantly into the model study, whereas in the prototype viscosity is of little influence even in diffusion and dissipation of energy. The speaker asked if there was proof that the upstream influence of the boundary could not be simulated by controlling the initial profile. The reply by Mr. Albertson was that this has been proven rather directly in open channel flow studies and indirectly in the wind tunnel. An attempt was made to lessen the required length of a channel by introducing upstream resistances such as cross bars in order to produce a logarithmic velocity profile. When this was done the desired profile was obtained immediately downstream, but the flow would then revert back to another equilibrium condition within a short distance downstream from the cross bars. When the approach was lengthened and the turbulence and velocity profile produced as in nature, the model behaved as desired. The speaker commented that they would like to try some similar experiments, as well as to try to sustain a temperature profile. On one occasion an initial
temperature profile was established and, by keeping the boundary at the proper temperature, it was possible to maintain the profile for the full length of the test section, roughly 30 feet. With a forced velocity profile there is at least a gradient to produce shearing forces even though the proper structure of turbulence may be lacking. It is more a question of the economics of wind tunnel construction since, if there is more upstream section, there must be a longer wind tunnel.