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PHYSICAL MODELING OF ATMOSPHERIC FLOW AND ENVIRONMENTAL APPLICATIONS

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Abstract - The philosophy of physical modeling of atmospheric flow is discussed with special emphasis on wind-tunnel simulation techniques. The governing equations of motion are analyzed for application of laboratory testing. Key similitude parameters such as Reynolds, Froude, Rossby, and Richardson numbers, as applied to wind-tunnel requirements, are discussed. Prevalent boundary condition requirements, i.e., Jensen's criterion and fully rough flow, are presented. Physics of atmospheric boundary layers are presented in the context of practical laboratory applications. The stack dispersion process of plume rise and diffusion into the atmosphere are discussed for near-field and far-field wind-tunnel simulations. Stack downwash, buoyant and non-buoyant stack processes are examined through experimental testing of full-scale cases and results are compared to wind-tunnel measurements made to simulate the results. Additionally, wind-tunnel results are compared to Gaussian-based computer models (ISCSTII and INPUFF). Comparisons illustrate that site-specific wind-tunnel results provide better assessment of the dispersion process than do the generic Gaussian models. Wind-tunnel testing is strongly recommended for complex geometry and/or unique topographic conditions.

1. Introduction

The use of wind tunnels to study the effects of wind near the earth's surface began more than a century ago when a scientist named Irminger [1] placed a model house in a small wind tunnel to measure wind pressure against the model. Since then, many attempts have been made to develop useful laboratory representations of the highly variable atmospheric winds. Early researchers employed tunnels derived from aeronautical wind tunnels that simulate steady wind flow situations such as the flight of aircraft through still air. In the last thirty years, wind engineering researchers have discovered that turbulent boundary layer flow over the floor of a wind tunnel provides reasonable laboratory simulation of "atmospheric boundary layer" (ABL) flow.

The ABL is a layer of air covering the earth, the thickness of which is determined by the height at which surface friction no longer affects the general flow of wind. Air in motion can be divided into “main flow,” where viscosity (fluid friction) plays a negligible part, and “boundary layer” flow where fluid friction is influential. The boundary layer is adjacent to a surface such as the surface of a planet. Over large bodies of water the boundary layer height may be as low as 200 meters, while above large cities it may be as high as 600 meters. Within this layer of air, motion is generally gusty or “turbulent,” with the wind changing speed and direction rapidly.

Several factors affect this motion: distance from the earth, surface roughness, and temperature. The average speed of the wind increases with the distance from the earth, while the intensity of the turbulence or gusting decreases. Increasing the roughness of the surface across which the air moves increases the turbulence. Surface roughness thus accounts for the differences in thickness of the layer for flow over water as opposed to flow over tall buildings. The temperature differences within the atmospheric boundary layer affect both wind speed and intensity of turbulence in complex ways and is classified by the stability of the atmosphere.

The variables given above render the flow in a boundary layer difficult to model mathematically and increase the desirability of simulating this flow in wind tunnels. The impetus for designing special “atmospheric boundary layer wind tunnels” (ABLWT) came from the desire both to do basic research on turbulence and turbulent diffusion and to study the effects of wind on structures (Irminger’s house, etc.). During the past twenty years, the study of diffusion of gases in the atmosphere has received increased attention.

In 1979 the U.S. National Bureau of Standards called attention to the need for studying air flow at very low velocities such as those that occur in stack dispersion. “National concern with problems of the environment and occupational health and safety,” the Bureau elucidated, “have imposed requirements for instrumentation and calibrations that would provide for more accurate air flow measurements at very low velocities.” Facilities that can perform these measurements must provide U.S. and world technology with needed data on “low Reynolds number flows, boundary layers, flow stability, turbulence, and fluid mechanical modeling.” Where wind engineers had previously focused on how winds affect structures, they now increasingly concern themselves with calibrations, basic research, and applications to environmental situation, to address health and safety concerns in the workplace.

2. Physical Modeling Philosophy

Motivated by the desire to contribute to basic research on turbulence, to the development of instrumentation to measure air flow at low velocities of turbulence, and to applied research on environmental pollution, particularly the dispersion of gaseous pollutants in an atmospheric boundary layer, the UC Davis ABLWT was designed and build in 1979.

Since the ABLWT was specifically designed to simulate naturally turbulent boundary layers, such as wind flow near the surface of the earth, the ABLWT required a long flow development section to produce a mature turbulent boundary layer at the test section, and a flow that varies significantly from the test-section floor to the ceiling.

In designing the ABLWT, use of previous research on turbulent boundary layers were utilized. Using experiments conducted by Nikuradse [2, 3] on flow in rough-walled pipe, Sutton [4] and Schlichting [5], among others, formulated a logarithmic wind profile law. Jensen [6] and other observed that a neutrally stratified ABL also obeys the logarithmic law:

$$\frac{\overline{u}(z)}{u*} = \frac{1}{k} \log \frac{z}{z_0} \tag{2.1}$$

where $\overline{u}(z)$ is the time averaged velocity, a function of the height z; z is the height above the surface; $u*$ is friction velocity; k is von Kármán's universal constant; and z_0 denotes the equivalent roughness height. From this equation and the work of Jensen one is able to determine what types of surface roughness should be used in the wind tunnel for proper simulation of various types of natural wind flow.

The structure of the ABL is complex and difficult to simulate. The inner layer, close to the surface of the earth, is two-dimensional in character, while the outer layer, further from the earth, is three-dimensional since it is affected by the "Coriolis force," a rotational force that creates a spiral effect, known as the Ekman Spiral [7], as the distance from the earth increases. This spiral effect cannot be modeled without rotating the wind tunnel, which is impractical. Consequently, only the first 100 meters adjacent to the earth can be modeled in a meaningful manner.

In the 1960's, Cermak [8-13] and Davenport [14, 15] and their associates have shown that wind tunnels can model the ABL. Many have applied the problem of modeling the atmospheric boundary layer by laboratory simulation with some degree of success [16-18]. Arya and Plate [19] have shown that the Monin and Obukhov [20] similarity theory offers a good foundation on which to base modeling of a stable stratified atmospheric boundary layer. As a result there are a large number of studies that have been conducted. Some good discussions of these classical cases are given in Monin and Yaglom [21], Lumley and Panofsky [22], and a basic review of the atmospheric layer in Monin [23]. From the similarity theory of Monin and Obukhov [20] the surface layer can be modeled if planar homogeneity exits. A detailed review of the implications of homogeneity to the similarity theory is given by Calder [24].

However, exact modeling of the entire ABL is not possible. By selecting certain similitude parameters that need not be strictly matched and relaxing these requirements, one can obtain good laboratory results for special type atmospheric flows. The similarity criteria can be obtained from the equations of motion for the particular flow problem by nondimensionalizing the equations. As a result the nondimensional equations will yield similitude governing parameters as coefficients of the equations of motion.

If horizontal and vertical geometry is preserved it will result in an invariant nondimensional transformation of the conservation of mass[1]

[1] Cartesian tensor notation and Einstein summation convention is used.

$$\frac{\partial u_i}{\partial k_i} = 0 \text{ and } \frac{\partial \rho}{\partial t} + \frac{\partial(\rho u_i)}{\partial x_i} = 0 \tag{2.2}$$

Nondimensionalization of the time averaged turbulent momentum equation yields the criteria for dynamic similarity. The time averaged momentum equation is

$$\frac{\partial \bar{u}_i}{\partial t} + \bar{u}_j \frac{\partial \bar{u}_i}{\partial \breve{x}_j} + \varepsilon_{ijk}\Omega_j \bar{u}_k = -\frac{1}{\rho_\circ}\frac{\partial \bar{p}}{\partial x_i} - \frac{\Delta \bar{T}}{\bar{T}_\circ} g\delta_{i3} + \nu_\circ \frac{\partial^2 \bar{u}_i}{\partial x_k \partial x_k} + \frac{\partial\left(\overline{-u_j u_i}\right)}{\partial x_j} \tag{2.3}$$

where the dependent variables are represented by mean (quantity represented by the bar over the variable and fluctuating values. The Boussinesq density approximation is made thus limiting the application of the equation to flows of $\Delta\bar{T} << \bar{T}_\circ$ where $\bar{p}$ is the deviation of pressure from the atmospheric pressure associated with $\rho_\circ$. Using,

$$\hat{\bar{u}}_i = \bar{u}_i / u_\circ \quad ; \quad \hat{u}'_i = u'_i / u_\circ \quad ; \quad \hat{x}_i = x_i / L_\circ \tag{2.4}$$

$$\hat{t} = t u_o / L_o \quad ; \quad \hat{\Omega}_j = \Omega_j / \Omega_o \quad ; \quad \hat{\bar{p}} = \bar{p} / \rho_o u_\circ^2 \tag{2.5}$$

$$\Delta\hat{\bar{T}} = \Delta\bar{T} / (\Delta\bar{T})_o \quad ; \quad \hat{g} = g / g_o ; \quad \hat{\bar{\varphi}} = \frac{\bar{\varphi}}{\varphi_\circ} \tag{2.6}$$

to nondimensionalize the turbulent momentum equation yields:

$$\frac{\partial \hat{\bar{u}}_i}{\hat{t}} + \hat{\bar{u}}_j \frac{\partial \hat{\bar{u}}_i}{\partial \hat{x}_j} + \underbrace{\left[\frac{L_\circ \Omega_\circ}{u_\circ}\right]}_{2} 2\,\varepsilon_{ijk}\hat{\Omega}_j \hat{\bar{u}}_k$$
$$= -\frac{\partial \hat{\bar{p}}}{\partial x_i} - \left[\underbrace{\frac{\Delta\bar{T}}{\bar{T}_o}\frac{L_o g_o}{u_o^2}}_{2}\right] \Delta\hat{\bar{T}}\,\hat{g}\,\delta_{i3} + \underbrace{\left[\frac{\nu_o}{u_\circ L_\circ}\right]}_{3} \frac{\partial^2 \hat{\bar{u}}_i}{\partial \hat{x}_k \partial \hat{x}_k} + \frac{\partial\left(\overline{-\hat{u}_j{}' \hat{u}_j{}'}\right)}{\partial \hat{x}_j} \tag{2.7}$$

Three dimensionaless parameters results as coefficients for the nondimensionalization of the momentum equation. In order to maintain proper dynamics similarity these three similitude parameters must be matched. These three parameters are known as

(1) Rossby number: $R_o = u_\circ / (L_\circ \Omega_\circ)$; (2.8)

(2) Bulk Richardson number: $R_i = \left[\left((\Delta\bar{T})_o / T_o\right)\right]\left[L_\circ g_\circ / u_\circ^2\right]$; (2.9)

(3) Reynolds number: $R_e = u_\circ L_\circ / \nu_\circ$; (2.10)

The time averaged conservation of turbulent energy equation is, neglecting radiation and assuming constant fluid properties,

$$\frac{\partial \overline{T}}{\partial t} + \overline{u}_i \frac{\partial \overline{T}}{\partial x_i} = \left[\frac{\kappa_\circ}{\rho_\circ c_{p\circ}}\right] \frac{\partial^2 \overline{T}}{\partial x_k \partial x_k} + \frac{\partial\left(-\overline{\hat{\theta}' \hat{u}_i'}\right)}{\partial x_i} + \frac{\overline{\phi}}{\rho_\circ c_{p\circ}} \tag{2.11}$$

where $\overline{\phi}$ is the dissipation function. Nondimensionalizing, as for the momentum equation, it becomes:

$$\frac{\partial \hat{\overline{T}}}{\partial \hat{t}} + \hat{\overline{u}}_i \frac{\partial \hat{\overline{T}}}{\partial \hat{x}_i} =$$

$$\underbrace{\left[\frac{\kappa_\circ}{\rho_\circ c_{p\circ} \nu_\circ}\right]}_{4} \left[\frac{\nu_\circ}{L_\circ u_\circ}\right] \frac{\partial^2 \hat{\overline{T}}}{\partial \hat{x}_k \partial \hat{x}_k} + \frac{\partial\left(-\overline{\theta' u_i'}\right)}{\partial x_i} + \frac{\overline{\phi}}{\rho_\circ c_{p\circ}} + \left[\frac{\nu_\circ}{u_\circ L_\circ}\right] \underbrace{\left[\frac{u_\circ^2}{c_{p\circ}\left(\Delta \overline{T}\right)_\circ}\right]}_{5} \hat{\overline{\varphi}} \tag{2.12}$$

Here two additional similarity parameters results:

(4) Prandtl number: $P_r = \nu_\circ \rho_\circ c_{p\circ} / \kappa_\circ$ (2.13)

(5) Eckert number: $E_c = u_\circ^2 / c_{p\circ} \left(\Delta \overline{T}\right)_\circ$

(2.14)

If these two parameter criteria are satisfied then thermal similarity exists. For wind-tunnel simulation in air the Prandtl number criterion is automatically satisfied and the Eckert number is only important in compressible flow.

For correct simulation of the ABL pressure distribution (on various objects), in wind-tunnel modeling, Jensen [6] observed that the roughness height ratio in the wind tunnel to that of the planetary boundary layer must be equal to a characteristic length of each, i.e.,

$$z_{\circ m} / z_\circ = L_m / L \tag{2.15}$$

Thus the geometric scaling of the boundary condition also must be satisfied as stated by Jensen. If the other similitude parameters are also satisfied then dynamic similitude will prevail.

Accordingly, geometric similarity is usually maintained between full-scale and model flows. Also, since the atmospheric flow over the surface of the earth has negligible pressure gradients over short horizontal distances, the wind tunnel also must have zero-pressure-gradient flow in the flow direction. This is obtained by having a false flexible ceiling in the wind tunnel and adjusting it to different heights for different floor roughnesses, which in turn model different surface topography, such as oceans, rural areas, and urban areas, to maintain the zero-pressure-gradient condition.

In addition to meeting these desirable similitude criteria, it was also necessary to develop a mature turbulent boundary layer within the tunnel. This is usually accomplished by one of two methods. The first method involves building a long test section to develop a boundary layer of mature turbulent structure. The second method is to use turbulent tripping fencing and roughness elements at the entrance of the wind tunnel to artificially create a "boundary-layer"-like velocity profile. The latter method usually does not produce mature turbulent flow because basic flow variables change fairly rapidly with distance downstream from the perturbating devices. Therefore, the UC Davis ABLWT facility has a long flow development section.

The geostrophic wind is the wind above the ABL and it is not analogous to the free-stream velocity in the wind tunnel due to the three-dimensional aspect of the ABL. Wind-tunnels studies are only valid for simulation of the surface layer of the planetary (or atmospheric) layer. Since this layer is essentially independent of the geostrophic wind and the Ekman spiral effect, it can be modeled without matching Rossby number.

For neutral ABL surface layers, Monin and Obukhov [20] developed a theory which uses only variable parameters defined at the ground surface, i.e., the surface roughness height, $z_\circ$ and friction speed, u_*, to entirely describe the layer. The surface layer extends up to a height of approximately 100 meters. Effects due to a nonneutral atmosphere (stable or unstable) can be simulated to some extent by cooling and heating the wind tunnel floor and/or ceiling.

3. Facility and Equipment

The ABLWT Facility – The facility is an open-return type with fan blades pulling air through the tunnel. The tunnel, which has an overall length of 22 meters, is composed of four sections: the entrance, the flow developing section, the test section, and the diffuser section, as shown in Fig. 1.

The entrance section is elliptically shaped to provide the incoming flow with a smooth contraction area for minimizing the freestream turbulence. To reduce large-scale pressure fluctuations of the flow and limit the size of airborne particles entering the wind tunnel, the contraction area is followed by a commercially available air filter. After the air filter, a honeycomb flow straightener is used to reduce large-scale turbulence.

Fig. 1 Schematic diagram of UC Davis ABLWT showing cross-sections of entrance (Section A-A), test section with three-dimensional traversing mechanism (Section B-B), and the diffuser-power drive system (Section C-C)

The flow development section is 12.2 meters long and is used to produce a mature turbulent boundary layer at the test section. Four spires placed at the beginning of this section and surface roughness elements placed throughout its length are used to enhance the thickening of the boundary layer to a height of about one meter at the test section. The flow developing section has an adjustable false ceiling and diverging walls, to provide zero-pressure-gradient flow.

The test section is three meters in streamwise length by 1.7 meters high by 1.2 meters wide. A framed Plexiglas door provides access to and allows observation of the test section. The test section ceiling also is adjustable to permit zero-pressure-gradient flow over its length. A three-dimensional probe traversing system provides accurate and fast sensor placement and can be moved over a large portion of the test section volume. To minimize flow disturbances the traversing mechanisms is aerodynamically shaped with aerofoil struts. Centerline wind speeds within the test section can be varied from 1 to 10 m/s.

The 2.44 m diffuser section allowed a continuous transition from the rectangular cross section of the test section to a circular cross section for the fan. The eight-blade, fixed-pitch, 1.83 m-diameter fan is driven by a 56 kW (75-hp) DC motor with controller. The facility is described in White [25].

<u>Velocity Measurements</u> – A “Dantec” Low Velocity Flow Analyzer and Thermo-Systems, Inc. (TSI), hot-wire anemometary are used for all velocity and turbulence measurements. The “Dantec” sensor was factory calibrated; additionally, a single hot-wire probe (TSI-1210, T1.5) was used to verify the “Dantec” calibration. “Dantec” probe and hot-wire anemometer measurements were found to have an inherent uncertainty of 5%, based upon laboratory calibrations using a TSI model 1125 calibrator unit.

<u>Three-dimensional Traversing Mechanism</u> – The probe was vertically mounted on the platform of the three-dimensional traversing mechanism in the test section. The electronic output of the probe-traverse mechanism was connected to three potentiometers, one for each of the three directions, x, y, and z. As the traverse would change position, the voltage differential across the potentiometers would vary. By using a digital voltmeter, it was possible to identify the position of the probe in all three directions. The “Dantec” probe was positioned at specified locations (i.e., exhaust fan heights), and the flow was digitally sampled over a 60-second period for velocity and turbulence measurements. The mean velocity and turbulence data were automatically analyzed on line. The “Dantec” low velocity analyzer displayed the mean and root-mean-square (rms) velocities digitally averaged over the 60-second period. The uncertainty associated with these measurements and subsequent calculations are specified by Dantec to be 5%.

<u>Concentration Measuring Equipment</u> – Wind-tunnel experiments are an effective means by which to evaluate the dispersion of effluents from building stacks or exhaust fans. Experimental analysis of plume dispersion cases for the present work was carried out by two methods: i) flow visualization using smoke composed of burned mineral oil; and, ii) gas-concentration-measurements made by a hydrocarbon analyzer using ethane as a tracer gas.

Flow Visualization – Smoke visualization tests were used to establish the location of the recirculation zones, or “cavities,” formed at the leading edge of building surfaces (see Fig. 2). Smoke was horizontally injected to follow a streamline near the leading edge and a recirculation “bubble” eight was determined from the observation of the smoke streamline patterns. Knowledge of the extent of recirculation is considered important since any stack enveloped by the recirculation zone would release effluent that would not be properly dispersed into the atmosphere, or, more seriously, may be drawn into the air intakes.

Fig. 2 Flow patterns around a rectangular building

Flow visualization proves valuable in predicting average plume dispersion trajectories and characteristics of the maximum plume envelope. This is achieved through the use of a video camera (COHU, model 4815) and a video-cassette recorder (Panasonic, model AG-1950) as a means of videotaping the dispersion of smoke in the wind tunnel. The taping is conducted over a long enough period of time (i.e., several minutes) to give a good representation of the fluctuating plume. Data are reduced by taking large number of plume trajectories and positions (i.e., fifty or more) directly from the screen of a Sony Trinitron color video monitor (model PVM-2030). These data outlined the area where smoke is observed to be present.

Hydrocarbon Analyzer−A Beckman 400A Hydrocarbon Analyzer is used to measure qualitatively the dispersion of building exhausts. The hydrocarbon analyzer system (see Fig. 3) is composed of: (1) a tracer gas injection; (2) a three-dimensional traversing sampling mechanism; (3) a flame-ionization hydrocarbon analyzer; and, (4) an analog-to-digital data acquisition system. All lines in the system that carry either the tracer gas or the air and tracer-gas sample mixture are 0.63 cm (1/4 in) refrigeration grade copper tubing, since copper does not absorb or produce significant quantities of hydrocarbons. The tracer gas injected through the modeled exhaust stacks is 97.5% ethane for neutrally buoyant emissions. The air and ethane mixture, or simulated exhaust plume, downstream of the stack in the wind-tunnel test section was sampled at specific critical locations (building entrances, air intakes, etc.) to determine the level of dispersion.

Fig. 3 Schematic diagram of Beckman 400A Hydrocarbon Analyzer System connected to the ABLWT to measure concentration of trace amounts of ethane gas in air.

Downstream of the stack, the ether-air mixture is sampled isokinetically at specific critical locations called receptors, e.g., air intakes, building entrances and courtyards, etc. The sample is then burned in the hydrocarbon analyzer with a mixture of pure air and 40%

hydrogen and 60% nitrogen. An analog-to-digital acquisition program samples the fluctuating output voltage from the analyzer with a frequency of 300 samples per second for a total of 27,000 individual voltage measurements to produce one averaged value (i.e., a sampling time of 90 sec). The time-averaged voltage is then converted to parts per million (ppm) concentration of ethane in air. Calibration of the analyzer, with two known samples of ethane-air mixtures, produces a linear relationship between the output voltage and the concentration. For each location, between two and three samples generally are taken to produce an average value of concentration at that location.

The continuous injection of ethane into the wind tunnel causes the background level of concentration of hydrocarbons to increase with time. To account for this effect the increase was considered to be linear over time and consequently background concentrations are taken at the beginning and the end of each testing session. Then, each sample value is 'corrected' by subtracting the appropriate background hydrocarbon concentration, determined from the linearly increasing background concentration.

4. Similitude Criteria

To model plume dispersion in an ABLWT the most important similarity criteria must be met. Additionally, it is necessary to model the characteristics of naturally occurring wind, and the dynamic and thermal properties of the exhausted plume.

Since some parameters such as gravity, g, or the kinematic viscosity of air, v, can not be scaled, similarity criteria are often conflicting in some sense or can not be simultaneously matched for all full-scale parameters. Therefore, it is necessary to identify certain similarity criteria that are considered less influential than other more important ones.

Local Wind Characteristics

Wind-Tunnel Turbulence – An accurate simulation of the ABL can be achieved only if the wind-tunnel boundary layer is also turbulent. To create a turbulent boundary layer the surface has to be aerodynamically rough; i.e., the roughness Reynolds number, Re_z, has to be greater than 2.5, or

$$Re_z = \frac{u_* z_0}{\nu} > 2.5 \qquad (4.1)$$

The UC Davis wind tunnel satisfies this condition. For a freestream wind-tunnel velocity of U_∞=3.8 m/s the following values have been measured: friction velocity $u_* = 0.24\,\mathrm{m/s}$ and roughness height $z_0 = 0.0025\,\mathrm{m}$. Thus, the calculated roughness Reynolds number is 40, well above the 2.5 criterion.

Mean Velocity Profile – The relationship for the mean velocity, u, versus height, z, in the wind-tunnel boundary layer flow also should be represented by the power-law, known to exist in full scale, which is given by:

$$\frac{u}{u_\infty} = \left(\frac{z}{\delta}\right)^\alpha, \qquad (4.2)$$

where δ is the boundary-layer height, u_∞ is the inviscid speed (at height δ) and α is the power-law exponent. The wind-tunnel flow can be conditioned such that the exponent α will closely match the full-scale value of α. For the present case studies, Fig. 4 displays a ABLWT mean velocity profile, and α is equal to approximately 0.3, the tunnel value is approximately the same.

In the lower 20% of the boundary layer the velocity profile must also agree with the logarithmic mean velocity relationship,

$$\frac{u}{u_*} = \frac{1}{\kappa} 1n\left(\frac{z}{z_0}\right), \qquad (4.3)$$

where κ is von Kármán's constant, which is equal to about 0.4.

The scaled model is desirably contained within this layer. For a boundary layer height of approximately one meter in the test section, the depth of this layer is 0.2 meter and corresponds to a full-scale height of 30m to 50m depending on the scale of the model. The maximum stack height considered in the current case studies is 40m (above ground level), i.e., within the logarithmic layer region. Also, this region of the ABL is relatively unaffected by the Coriolis force, and is the only region that can be modeled accurately by ABLWT.

Turbulence Intensity Profile – Turbulence intensity profiles, u'/u versus z, provide an indication of the variation of streamwise turbulence through the shear layer. The profile for the wind tunnel should agree reasonably well with the full scale, especially within the lower 20% of the boundary layer where testing is carried out. Maximum values of the UC Davis wind-tunnel turbulence intensity range from 35% to 40%, similar to those values found in full scale in the surface layer as shown in Fig. 5.

Similarity of Scaled Model

Geometric Scale – Depending on the size of the wind tunnel, the roughness height and the power-law index α, the scale ratio for geometric dimensions of the model may be determined. If possible, the integral scale length ratio, full scale to wind tunnel, should be matched, thus setting the scale. Typical geometric scales vary from 1:100 to 1:1000. The model used in this analysis was scaled 1:360 for the first case study and 1:300 for the second case study, which match the estimated full-scale integral length scale.

Fig. 4 Theoretical mean velocity profile of full-scale case with surface roughness, $z_\circ$ equals 5 cm (solid line). Experimental data are taken from UC Davis ABLWT 1:192 simulation for a geostrophic wind speed of 40 m/s.

Fig. 5 Theoretical longitudinal turbulence intensity profile of full-scale case with surface roughness, $z_\circ$, equals 5 cm (solid line). Experimental turbulence data are taken from UC Davis ABLWT 1:192 simulation of full-scale for geostrophic wind speed of 40 m/s.

Scaling of Wind Speed – Full-scale wind speeds of interest in diffusion studies are usually in the range form 3 to 20 m/s. Depending on specific test conditions, scaling of the natural wind may be based on equality of stack momentum or densimetric Froude number. Both quantities will be discussed later in this section; however, matching either similitude parameter results in wind-tunnel speeds in the range of approximately 1 to 7 m/s. Also, regardless of the method chosen to establish a velocity scale, some mechanical limits imposed by the wind-tunnel facility itself may further reduce the range of operating speeds.

Most wind tunnels have a minimum operating speed that gives satisfactory performance. At very low speeds, inlet flow conditions can introduce small perturbations. The resulting flow instabilities may effect the velocity spectra. The minimum operating speed for the UC Davis ABLWT is considered to be 0.5 m/s.

The maximum operation speed of wind tunnels is governed by the physical limits of the electric motor that drives the fan to introduce flow. The 56 kW (75 HP) motor at UC Davis produces a maximum operating speed of 10 m/s.

Building Reynolds Number – The building Reynolds number Re_H, represents a ratio of inertial to viscous (or frictional) forces over the surface of the building. It is often used as a similarity parameter that should be matched between the full scale and the model to insure similitude. The Reynolds number is given by:

$$Re_H = \frac{u_H H}{\nu}, \tag{4.4}$$

where H is the building height, u_H is the wind speed at that height, and ν is the kinematic viscosity of air. Since wind-tunnel simulations use the same fluid, air, as in full scale, the full-scale Reynolds numbers exceed those of the model by several orders of magnitude due to scale reductions; therefore, it is impossible to exactly match the building Reynolds number. However, for the purpose of concentration measurements, flow above a critical building Reynolds number value of 11,000 is known to be Reynolds number independent and will accurately model full-scale buildings and structures.

It can be shown experimentally that the critical value for flow independence is conservative and smaller building Reynolds numbers may be acceptable. Past wind-tunnel simulations at UC Davis involved a series of tests to establish Reynolds number independence. In the case of dispersion studies, this was achieved by making concentration measurements for what represents high and low wind-tunnel speeds relative to stack exhaust speed, and showing that ground-level concentrations were relatively unaffected by the extremes of this ratio for values of building Reynolds number as low as 3500.

Scaled Plume Characteristics

Internal Stack Reynolds Number – Stack emissions in full-scale are usually turbulent, while modeled internal stack flows might be laminar. Matching the full-scale stack Reynolds number in wind-tunnel simulations is not always possible. However adequate similarity is achieved by ensuring that the tunnel stack flow also is turbulent. Stack flow will be turbulent as long as the stack Reynolds number, Re_s, is above a critical value, or

$$Re_s = \frac{u_s D_s}{\nu} > 2300\,, \tag{4.5}$$

where u_s is the stack exit velocity and D_s the stack inside diameter. The stack flow should be tripped to enhance turbulence if the stack Reynolds number is less than 2300.

Plume Buoyancy – The square of the densimetric Froude number,

$$(Fr)_d^2 = \frac{\rho_a U_w^2}{(\rho_s - \rho_a) g D_s} = \frac{\rho_a U_w^2}{\Delta\rho g D_s}\,, \tag{4.6}$$

represents the ratio of inertial to buoyancy forces, where u_w is the wind speed at stack height, $\Delta\rho$ the density difference between exhaust gases and the ambient atmospheric air density, ρ_a, and g the gravity. If emissions are neutrally buoyant, the densimetric Froude number similarity will not be considered.

The standard Froude number is relatively straight-forward to duplicate in a wind-tunnel model; however, strict adherence to it can result in difficulties due to extremely low velocities if the critical value of the Reynolds number for Reynolds-number-independent flow also is to be met. For example, in order to match large full-scale Froude numbers for a model scale of 1:300, it is necessary to decrease the wind-tunnels mean flow speed. As shown previously, lower mean speeds results in smaller Reynolds numbers and, possible, laminar flow, which is unacceptable.

Therefore, the use of the densimetric Froude number rather than the conventional Froude number,

$$(Fr_d)^2 = \frac{U_w^2}{g D_s}\,, \tag{4.7}$$

can result in model wind speeds of approximately 50% higher. This is directly related to the fact that for buoyant plumes, the ratio of stack gas density to ambient air density is not unity. Recent studies at UC Davis examining buoyant heated exhausts have modeled plume rise by matching full-scale and wind-tunnels buoyancy length scales, L_B [26],

$$L_B = \frac{u_s \Delta\rho D_s^2 g}{4\rho_a U_w^3}\,, \tag{4.8}$$

the buoyancy length scale also may be represented as:

$$L_B = \frac{D_S u_S}{4U_w} \frac{1}{(Fr)_d^2}, \qquad (4.9)$$

thus factoring in both the densimetric Froude number and the plume velocity ratio, u_s/U_w.

Plume Velocity Ratio – To maintain a correct ratio of plume exhaust velocity, u_s, to that of the ambient flow, U_w, the following requirement has to be met:

$$\frac{u_S}{U_w} = \text{constant} . \qquad (4.10)$$

Taking into account the limited wind-tunnel operating velocities, the wind speed at stack height, U_w, and/or the stack exit velocity, u_s, in the tunnel can be varied, such that their ratio remains equal to that of the full-scale case.

Plume Momentum Ratio – The plume momentum ratio represents the ratio of vertical to horizontal momentum. Maintaining of a correct ratio in the wind tunnel to the one found in the full-scale case requires that:

$$\frac{\rho_S D_S^2 u_S^2}{\rho_a L^2 U_w^2} = \text{constant} , \qquad (4.11)$$

where ρ_s and ρ_a are the gas densities of the stack and airflow, and L is a vertical length scale.

For a non buoyant stack exhaust, ρ_s is equal to ρ_a, and therefore*:

$$\left(\frac{D_S u_S}{LU_w}\right)_{FS} = \left(\frac{D_S u_S}{LU_w}\right)_{WT} . \qquad (4.12)$$

With length scale λ, defined as,

$$\frac{L_{WT}}{L_{FS}} = \frac{1}{\lambda}, \qquad (4.13)$$

this relationship reduces to:

* If exact scaling of stack diameter is maintained then this expression reduces to $(u_S/U_w)_{FS} = (u_S/U_w)_{wT}$ which is often used as a similitude parameter; however, this is only the case when exact geometric scaling is used.

$$(u_s)_{WT} = \frac{1}{\lambda}\frac{(D_S)_{FS}}{(D_S)_{WT}}\frac{(U_W)_{WT}}{(U_W)_{FS}}(u_S)_{FS}\,. \tag{4.14}$$

Let $(u_s)_{FS}$ be the critical stack speed for minimum, u_{crit}, and the flow-rate be $Q_{WT} = (u_s A_s)_{WT}$, with

$$A_S = \frac{\pi}{4}(D_S)_{WT}{}^2 \tag{4.15}$$

then, the required trace gas flow-rate in the wind tunnel, Q_{wt}, becomes:

$$Q_{WT} = \frac{\pi}{4}\frac{1}{\lambda}(D_S)_{WT}(D_S)_{FS}\frac{(U_W)_{WT}}{u_{crit}}(u_S)_{FS}\,. \tag{4.16}$$

Therefore, different full-scale wind speeds may be simulated in the ABLWT by adjusting the tracer gas flow rate, flow-rate. For testing purposes, adjusting the trace gas flow-rate is more convenient than changing the wind-tunnel velocity.

Concentration Measurement Scaling – Under similar atmospheric conditions, measured wind-tunnel concentrations may be related to those in the full-scale case by the following relationship:

$$\left(\frac{CU_w}{C_S u_S A_S}\right)_{FS}\lambda^2 = \left(\frac{CU_W}{C_S u_S A_S}\right)_{WT}, \tag{4/17}$$

where λ is the scaling factor and C_s is the concentration of the source. In this case, the concentration units are in mass of pollutant per volume of air. To convert volumetric concentrations (ppm), C_{vol}, as used in the present study, to mass per volume concentrations, the following relationship is used:

$$C(g/m^3) = C_{vol}(ppm)\frac{M_g}{M_a}\frac{p_a}{R_d T_a}10^{-3}\,. \tag{4.18}$$

Since the exhaust gas mixture has a molecular weight close to that of air and the exhaust temperature is close to the outdoor ambient temperature, volume fraction and mass concentration dilution’s are assumed to be equal.

5. Discussion of Selected Case Studies

Plume dispersion studies using mineral-oil-based smoke for flow visualization have been conducted in the UC ABLWT since 1987. Concentration measurements of plume dispersion began in 1988. More than twenty studies have been carried out since then, and two selected cases of particular interest are presented here. Case 1 addresses far- and near-field effects, such as those seen at roof level and close to the structure of interest. Results from this test are compared to Gaussian-based calculations generated by the U.S. EPA-approved Industrial Source Complex Short Term (ISCSTII) model, that predicts concentrations by Gaussian techniques. Case Study 2 addresses both the near vicinity of the stack, as well as a range over 800 meters around the stack. In this case study, the effluent is highly non-buoyant and results from these tests are compared to the U.S. EPA-approved Integrated Puff-dispersion model (INPUFF) that predicts pollutant concentrations at distances greater than 100 m form the source.

In the evaluation of stacks and exhaust fans, the local wind-speed distribution is very important, since the expected near-maximum wind speed at the stack height is issued to estimate the required stack exit velocity. Local wind characteristics are presented in a wind rose. The wind rose for Case Test 2 is shown in Fig. 6. This figure represents wind speed, direction, and frequency of occurrence. In its present usage, a “west” wind direction implies that the wind was from the west to the east. The wind-tunnel flow was conditioned to represent the atmospheric boundary layer semi-urban area and values of roughness height, z_o, and velocity profile exponent α, are similar to suburban settings which is the sistuation for both case studies.

In each of the two cases presented, an objective of the test will be stated, the appropriate analysis will be presented identifying those critical parameters to be simulated, and the results will be given, including a discussion of interesting findings and other points of interests.

6. Case Study 1: Near- and Far-Field Air Toxics Study of a Large Industrial Complex

Wind-tunnel studies and wind engineering calculations for pollutant dispersions from roof exhaust fans were carried out for a large proposed commercial-research industrial complex to be located near San Francisco, California. Wind-tunnel studies included flow visualization to establish qualitative characteristics of the buildings’ sites and stack plumes, and ethane tracer gas tests to establish quantitative pollutant concentrations at specific downwind locations. The ASHRAE model [27] was used analytically to predict concentrations (or dilution factors) in the near vicinity of the stack.

Assessing Risk from Toxic Air Contaminant Emission – An analytical model is commonly used to estimate the health risk due to toxic air contaminant emissions and also to estimate the potential for other (non-cancer) acute or chronic health effects. Four analytical steps are required: (1) hazard identification - determining the hazardous emissions resulting from a project; (2) dose-response assessment - evaluating the health effects of exposure to these emissions; (3) exposure assessment - estimating the possible level of exposure; and, (4) risk characterization - integration of the first three steps to estimate risk. Each step involves making assumptions, and each assumption involves inherent uncertainties.

Fig. 6 Annual meteorological “wind rose” for Lawrence Livermore National Laboratory, Livermore, California.