Controlling the Wind Climate Around Buildings

The wind environment may affect buildings and their surroundings. Engineers and architects must bear in mind that the wind influences both operating costs for buildings and the environmental quality of built areas.

EDWARD ARENS & JON PETERKA

IN DESIGNING BUILDINGS, civil engineers and architects should be aware of environmental wind effects and their control. A knowledge of the causes of wind, influences of topography and ground cover on local wind, and principal features of airflow around buildings is recommended. Designers should study windspeed distributions in the climatological record and use such knowledge to estimate the eventual windfield in the built environment. In this way they may ensure optimum living conditions in the area outside the building and optimum efficiency in operating the building.

Wind: Its Causes and Nature

The sun heats the earth unequally, generating pressure gradients that drive global, or synoptic, wind circulation. The pattern of wind circulation changes as the sun moves north and south with the seasons, and is affected by the position of mountain ranges and large bodies of water on the earth's surface. Temperate regions experience a number of typical wind patterns at any location during a season. These patterns are caused as air masses of different origin — such as maritime, continental, tropical or polar — are drawn over the region. The air masses and fronts that separate them will frequently incorporate such local wind phenomena as thunderstorms or tornadoes. The wind climate of a region may be predicted in terms of the probabilities with which these typical wind patterns occur. For example, average windspeeds in the continental United States tend to be stronger in the colder seasons when the frontal zone separating temperate and polar air masses moves southward from the Arctic.

In addition to synoptic winds caused by large scale weather patterns, there are predictable *local winds* that are produced by the particular features of a given terrain. In many coastal areas, the differential heating of land and water causes sea and land breezes. Figure 1 shows the pressure distribution and flow that cause daytime sea and night land breezes. The sea breeze tends to move inshore around midday as the land warms and causes the air above it to expand.

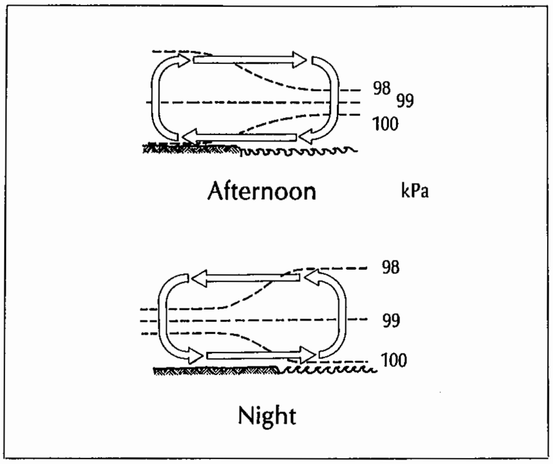

FIGURE 1. The pressure distribution and flow of daytime sea and nighttime land breezes.

Frictional resistance of the earth's surface often forces the incoming sea air to dam up. The air flow then forms a small scale front that progresses inland throughout the afternoon. In places where the temperature difference between land and water is small, the sea breeze layer will be shallow and wind velocities will be weak. Tall buildings along a waterfront can block such a breeze entirely. On the other hand, when the sea and land temperature difference is great, the sea breeze layer will be deeper and velocities much stronger. The San Francisco sea breeze is over 200 m deep, predictably exceeding 10 m/sec in the city throughout summer afternoons, and extending inland 60 km. At night this wind flow is reversed, but velocities seldom exceed 2 m/sec.

The radiant heating or cooling of inclined surfaces causes *slope winds,* another form of local wind. Such radiant heating and cooling produces temperature differences between the air above the slope surface and air at the same level some distance from the slope. Heated air will rise from the surface of hillsides during the day and cooled air will descend, or drain down, at night (see Figure 2). Daytime measurements on slopes surrounding the Inn Valley, Austria, found upward velocities parallel to the slope at 2-4 m/sec; at night there were somewhat lower downward velocities. Wind layer depth was 100-200 m.[1]

When slopes are arranged into a valley system, a combination of slope winds and temperature differences between the valley and the plain can form *valley winds.* These winds are generally stronger than slope winds; their wind velocities can reach up to 5 m/sec. The strongest valley winds are most commonly found in U-shaped valleys that are lined by high ridges. These valleys also open onto a broad plain that is considerably warmer or cooler than the head of the valley. Orientation of valleys with respect to the sun also affects wind velocity. Valleys that have a north-south orientation tend to have stronger daytime breezes due to their increased exposure to the sun.

Wind Over the Earth's Surface

The wind flowing along large-scale pressure gradients above the frictional influences of the earth's surface is known as *gradient wind.* At the lowest layers next to the surface, the gradient wind velocity is zero. The zone of velocity change from zero at the bottom to gradient wind velocity at the top is known as the earth's boundary layer. The depth of the boundary layer and the shape of the velocity

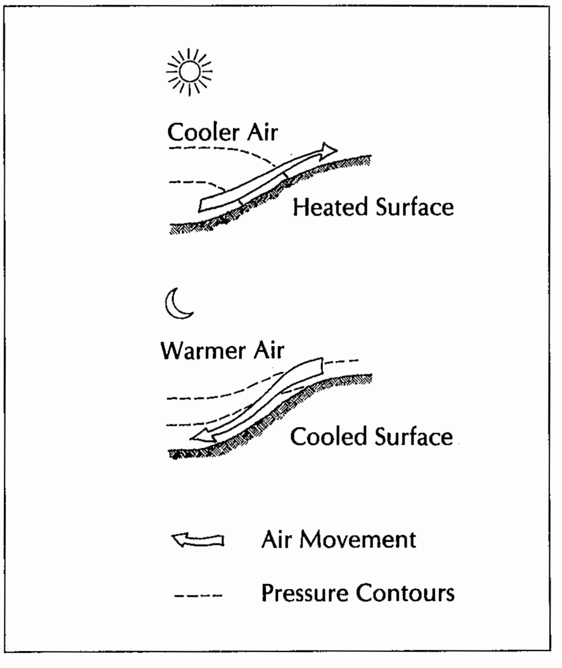

FIGURE 2. Daytime and nighttime flow of slope winds.

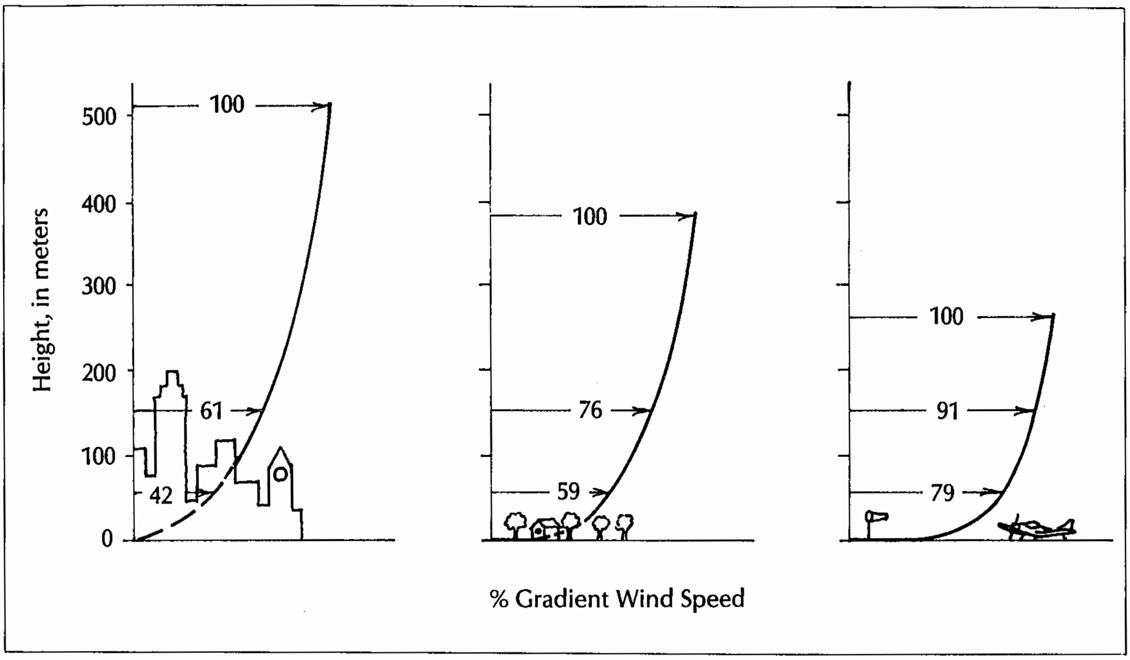

FIGURE 3. Boundary layers for neutral stability conditions from rough to smooth terrains.

profile within it depend on the roughness of the earth's terrain, and on the thermal stability of the atmosphere.

Figure 3 shows three boundary layers for neutral stability (strong wind) conditions. A rough urban surface causes a deeper boundary layer and lower velocity values at any given level within the boundary layer. In smooth terrain, such as at airport weather stations, the wind velocity at the standard anemometer height of 30 feet (10 m) is greater than in rougher terrains. This measured wind is also greater than the wind at pedestrian level at ground level in any terrain.

The profiles of these curves are commonly described as either logarithmic or exponential. In the region of constant shear, typically 100 to 300 m above the top of the roughness, the logarithmic law is correct:

$$U_z = \frac{U_*}{0.4} \log \left(\frac{z}{z_0} \right) \qquad (1)$$

where U_z is the velocity at height z; U_* is the friction velocity (a measure of shear); and z_0 is the roughness length (a measure of the roughness size). z_0 is constant for a given terrain, and U_* is constant across any given profile. Typical values of z_0 are given in Table 1 on the next page.[2]

In structural engineering the boundary layer up to the gradient height is often approximated with a power law with a constant exponent α. The relationship between the velocities at any two heights in the boundary layer is given by:

$$\frac{U_{z1}}{U_{z2}} = \left(\frac{z_1}{z_2} \right)^{\alpha} \qquad (2)$$

Values of α are also given in Table 1. Both representations of the mean velocity profile are commonly used by meteorologists, engineers and architects.

There are five different terrain categories — I = open water; II = open rural terrain; III = suburbs at considerable distance from towns with widely spaced buildings; IV = towns, densely built-up suburbs, rough or wooded terrain; and, V = centers of large cities — that are shown in Table 1. The boundary layer profiles predicted for these terrain categories will apply only if there is sufficient upwind distance of the terrain type for the develop-

TABLE 1

Surface Roughness Lengths & Power Law Exponents for Various Categories of Terrain

Terrain Category	Open Water I	Open Terrain II	Suburbs III	Towns IV	City Center V
z_o, in meters	0.005	0.07	0.30	1.00	2.50
α	0.10	0.14	0.20	0.25	0.35

ment of the particular boundary layer. The boundary layer above any local terrain will extend upward for a height approximately one percent of the distance to a change of terrain roughness upwind. Above that, there may be a remnant of the boundary layer persisting from the more distant terrain roughness type.[2]

These profiles apply to neutral atmospheres, such as those that occur during strong winds and during periods when the surface is not strongly heating or cooling the atmosphere. During strong heating from below, as for example on a sunny day with light winds, the atmosphere becomes unstable, bringing the gradient wind momentum downward. As a result, the surface wind will be stronger than it would be for a neutral atmosphere with the same gradient wind. Conversely, during night cooling of the ground and lower layers of air, the atmosphere becomes stable, and surface winds will be lower for a given wind than they would be in neutral or unstable atmospheres. This results in a predictable variation in daily wind speeds. Figure 4 gives a typical example of the daily course of wind over flat terrain.[1] Note that the wind at 70 m (210 feet) decreases somewhat in the morning as its momentum is absorbed in accelerating the lower layers of air.

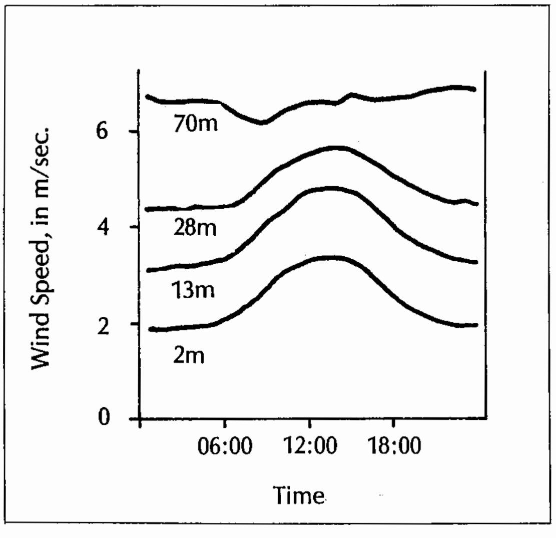

FIGURE 4. Typical daily course of wind over flat terrain.

Local topography has a pronounced effect on surface winds. Wind flow conforms to terrain, changing its strength, steadiness and direction as it passes over uneven ground. Figure 5 shows the velocity profiles of wind approaching a hill or ridge, at the crest and on its leeward side. There is strong wind acceleration near the surface at the top

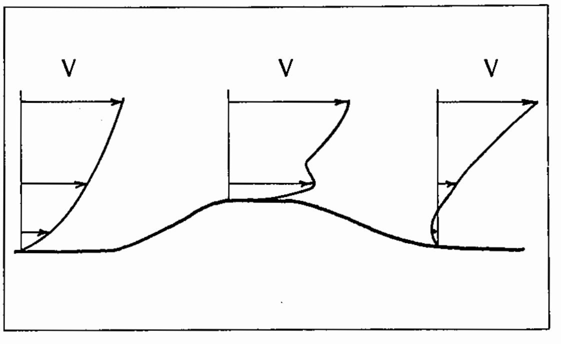

FIGURE 5. Wind velocity profiles to windward, on top of and to leeward of a hill or ridge.

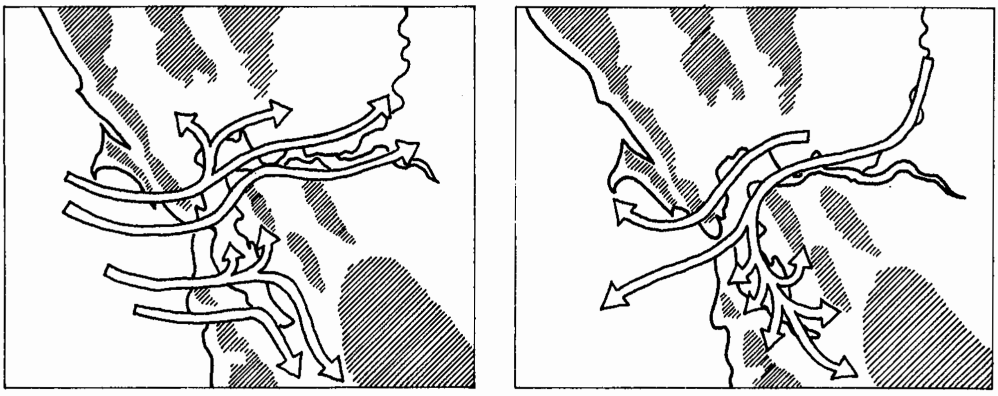

FIGURE 6. Typical surface wind flow patterns in the San Francisco Bay region.

of the hill, and also a wind flow reversal due to an eddy at low levels along the leeward side. The wind acceleration on the windward side of hills and ridges is fairly predictable, but the extent of shelter in the lee is highly variable, depending on the roughness of the hill and the stability of the atmosphere.

In addition, wind may be extensively channeled by regional topography. Figure 6 shows two typical wind flow patterns identified in the San Francisco Bay area.[3] High ground is noted in grey. Local areas of wind turning in excess of 90° to the gradient wind may be noted. This type of channeling occurs primarily when the atmosphere is stable, and the flows depicted extend upward roughly to the height of the surrounding terrain. Similar flow turning and channeling has been observed in street canyons.

Tall vegetation may reduce ground level wind substantially. Trees are very effective at absorbing wind energy rather than deflecting it (as do solid obstructions such as terrain and buildings). Two major categories of wind-reducing vegetation are a surrounding forest and an isolated windbreak. The effects of both of these forms of wind reduction have been studied extensively by agricultural and forestry researchers. Within a forest, the velocity is minimal near the center of mass of the foliage in the crown (approximately 0.75 times the height); in the absence of underbrush there is a small velocity increase among the tree stems. The shape of the wind profile in the forest is contingent on the type of the trees in the forest, their spacing and openings in the crown, and the distance from the edge of the stand from which ground level wind can penetrate. Figure 7(a) compares wind velocity profiles in a ponderosa pine stand to those profiles in the open,[4] and 7(b) shows the influence of foliage from seasonal wind measurements in a deciduous oak-beech forest.[1]

Figure 8(a) shows a cross section of the airflow near a screen of 50% porosity. Figure 8(b) shows the effect of varying porosity in shelter at ground level downwind.[1] A medium porosity of 40 to 50% has been found to provide the maximum distance of wind-sheltered area. A solid barrier will provide a greater wind reduction over a very limited distance downwind of the barrier, but beyond this distance (roughly three heights) it has less effect than screens of either open or medium porosity.

Additional belts downwind of each other have been found to have a slightly decreasing effect, presumably due to the increased turbulence in the lee of the first belts. Similarly, the sheltered zone leeward of a wide shelterbelt or forest is less extensive

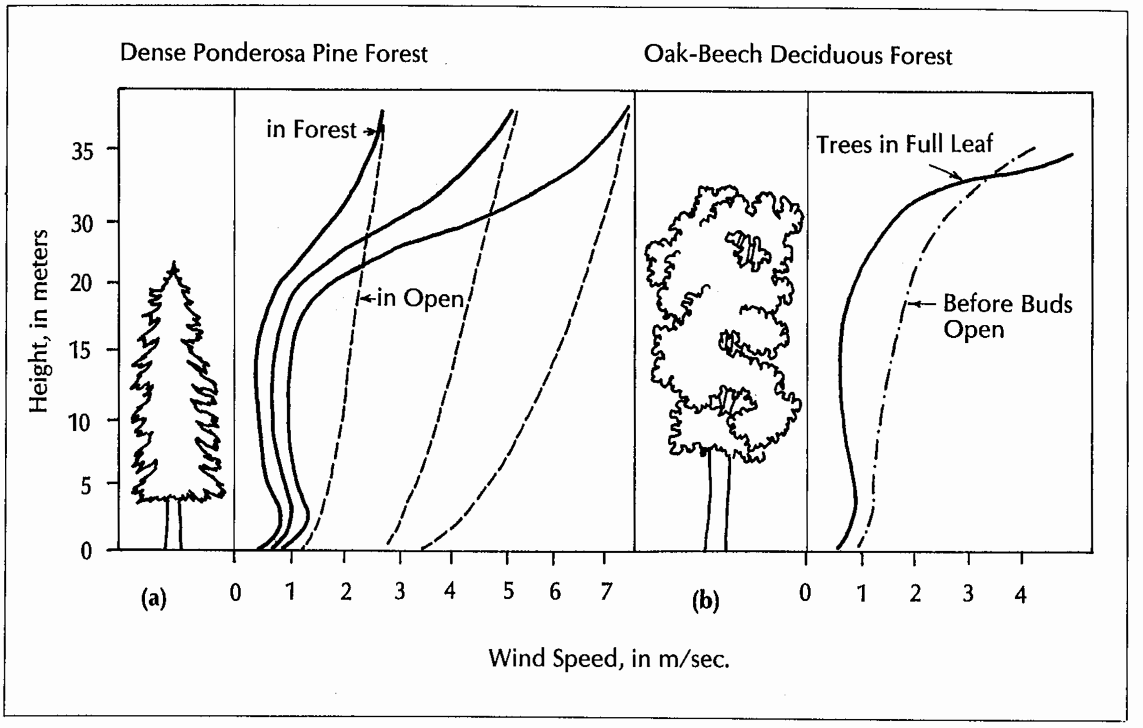

FIGURE 7. A comparison of wind velocity profiles at three wind strengths: (a) in a ponderosa pine forest vs. in the open; and, (b) a comparison of the average wind speeds between leafed and leafless forests.

than that behind a single permeable windbreak.

Wind Flow Around Buildings

The wind in urban areas is generally lower than in aerodynamically smoother rural areas (see Figure 3 on page 45.), but the local wind flows at pedestrian level around individual buildings are extremely variable, and may be much higher in these places than those in flat rural areas. This is because tall buildings may act as scoops that bring down high velocity air from aloft. Figure 9 shows the principal flow patterns around a building exposed to the wind.

Strong flows are found in the windward vortex, in which the direction at the surface is reversed from wind direction aloft; at the windward corners of the building; and in any passages or openings leading from the relatively high pressure zone on the windward side to the low pressure zone in the lee. The zone in the lee of the building has low wind velocity, often with the airflow going in the opposite direction from the approach wind. Similar flow patterns, known as "lee rollers," typically can be seen in street canyons when the wind crosses the street from the side.

While it is not possible to accurately predict the windfield within complicated building clusters without tests, estimates can be made for the surface wind environment for certain simple isolated buildings, and for some specific building clusters that have been previously studied. For an isolated rectangular building, the approximate maximum mean winds at the corners of the building may be anywhere from 0.8 to 1.0 times the mean velocity approaching the building at its top. Researchers at building research stations in the United Kingdom, France, and the Netherlands have studied other building shapes and typical building clusters and produced illustrations of commonly occurring wind phenomena, with generalized quantifications where possible.[5,6,7,8] For complicated geometries, it is difficult to make generalizations, and the only

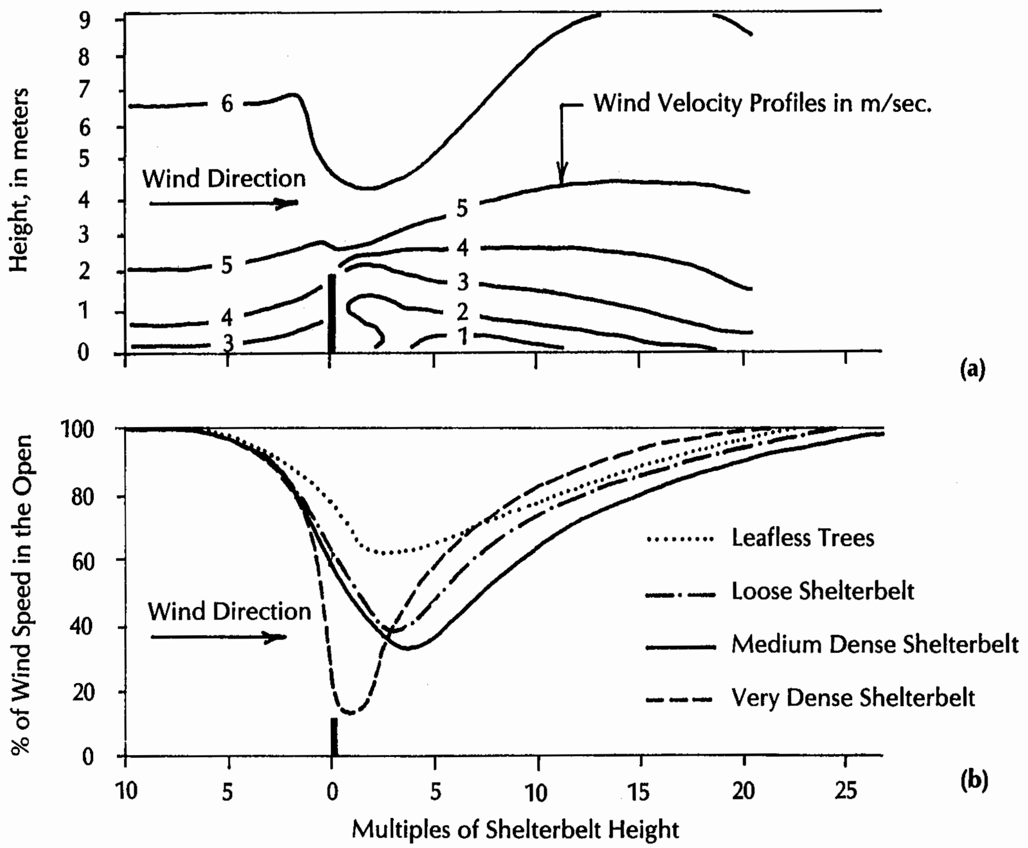

FIGURE 8. Wind velocity profiles around: (a) a shelterbelt of 50% porosity; and, (b) porosity vs. downwind shelter effect.

recourse at present is to use wind tunnel tests. The wind in built-up environments may be controlled at several scales, from the design of the surrounding buildings to devices specifically employed to provide local shelter.[9] Several factors should be considered in urban building design:

1. Large slab buildings should not be oriented in a direction normal to the prevailing wind to avoid downwash on the windward face. Circular and polygonal towers tend to have advantageous wind climates at ground level because of reduced downwash.

2. Tall buildings benefit from significant horizontal projections to break up downward-directed winds. From the point of view of wind control, the "ziggurat" or

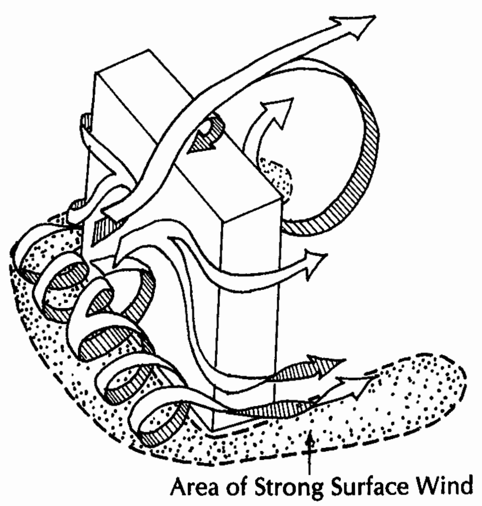

FIGURE 9. Principal wind flow patterns around a building exposed to the wind.

"wedding cake" designs of the 1930s through 1950s were better than the sheer slabs of the last two decades.

3. Large buildings placed at an angle to each other can form a funnel. This funnel can then accelerate the wind in the gap between the buildings. This effect, known as a *venturi*, will occur when buildings are over five stories high, have a combined length of over 300 feet, and have open areas in front of and behind the gap. Similar acceleration will occur when wide buildings overlap relative to the wind, so that the high pressure on the face of one building is channeled laterally to the low pressure area behind the other.

4. Important plazas, pedestrian thoroughfares, and building entrances should not be planned on the windward side or corners of tall slab buildings, since these areas are downdraft regions and exhibit accelerated corner flows. Well-known examples of wind-plagued plazas and entrances include the U.N. building in New York City and the John Hancock and Prudential buildings in Boston.

5. Openings through buildings near the ground, especially openings facing the prevailing wind, will experience strong winds unless revolving doors are used to prevent flow though the openings. The Earth Sciences Building at M.I.T., with its main entrances off a tunnel through the building at ground level, proved inaccessible in windy weather and required extensive ground level modification.

6. Vegetation and mechanical windbreaks may be used to absorb horizontal wind energy in pedestrian areas. There are a large number of windbreaks available for use in urban surroundings.[10] Such barriers are usually not effective at protecting large areas from the downdraft, or vertical, winds common in the vicinity of tall buildings.

There are also situations where it is desirable to encourage wind flow in cities. City planners in hot climates have investigated building spacing to maximize the natural ventilation available to the buildings,[11] and ventilation is also encouraged in areas near pollution sources such as highways or factories.

Wind Issues In Design

Natural Ventilation is the intentional displacement of air in buildings through windows, doors, ventilators or other devices under the occupants' control.[12] It is used to remove heat generated in buildings and to provide air movement to cool the occupants by convection. The airflow is induced by wind forces and thermal forces. Wind produces positive pressures on the windward face of the building and negative pressures on the leeward face. The building shape controls the pressures on the other faces. The pressure differences drive air through the building as estimated by the following formula:

$$Q = CAV \tag{3}$$

where Q is volumetric airflow, A is the free area of inlet or outlet openings, V is the wind velocity, and C is the effectiveness of the opening, depending on its shape and orientation relative to the wind. Common values range from 0.25 to 0.60.

The thermal buoyancy caused by temperature differences between the building interior and exterior produces the additional airflow:

$$Q = CA[h(T_i - T_o)]^{1/2} \tag{4}$$

where h is the difference in height between inlet and outlet, and C ranges between 0.09 and 0.12, depending on effectiveness of the opening, when Q is in m^3/sec and T in °C. Increasing the height and area of opening increases the airflow. Inlet and outlet areas should be nearly equal.

Some general rules for designing for natural ventilation are:[12]

1. Interior-exterior airflow systems should be designed to work regardless of wind direction. This may require using backup fans to counteract unfavorable windflow.

2. Openings cannot be obstructed by surrounding buildings, trees, etc. In such

cases, the initial velocities used for airflow calculation should be reduced to represent the velocity at the openings.

3. Openings are usually most effective when one or both are positioned low to move air through the occupied zone of the interior.

The placement of trees and shrubs can funnel and direct airflow around and through buildings.[13,14] Hedges and trees placed close to buildings can be used to create high and low pressure zones to force greater ventilation through building openings. Although there is little real data available for predicting natural ventilation, approximations and estimates can be obtained using rudimentary wind tunnel techniques.

Infiltration is the uncontrolled displacement of air through unintentional gaps in the building envelope. In cold weather, infiltrative air exchange accounts for roughly one-third of residential heating requirements. It is a function of exterior wind, and is most simply predicted by the crack method:[12]

$$Q = CA(\Delta P)^n \tag{5}$$

where C is a flow coefficient (the volumetric flow rate per unit length of crack) per unit pressure difference. ΔP is the interior-exterior pressure difference, and n is the flow exponent, with a usual value for building cracks of 0.65. Infiltration is roughly proportional to wind velocity when wind forces exceed thermal buoyancy forces. Infiltration can also be predicted with more sophisticated models that use as variables an empirically-determined whole building leakage area, the wind velocity and the temperature difference.[15] Trees and fences surrounding buildings have been shown to reduce wind pressures on buildings and significantly reduce infiltration rates.[16]

Mechanical Systems Efficiency. Wind influences the energy requirements of mechanical systems by causing the recycling of exhaust air from cooling towers, and by reducing the thermal efficiency of cooling equipment and heat pumps. There does not appear to be much published literature on the magnitude of wind-induced mechanical inefficiencies although these inefficiencies can be serious. There are highrise buildings in San Francisco topped with cooling towers that have been reported to lose 70% of their cooling capability during the daily sea breeze. The problems are usually associated with the design of the architectural enclosure surrounding the cooling tower. Such enclosures can encourage the wind to circulate within them, trapping the moisture laden exhaust air and returning it to the cooling tower supply. However, wind will also reduce the design efficiency of unenclosed open-sided cooling towers by disturbing the flow of cooling water within the tower. Effective enclosures should both reduce the wind within the cooling tower and prevent a flow pattern around the tower that returns the exhaust to the tower. This may be done by providing the enclosure with localized openings.

Wind pressures also affect mechanical systems at their inlets and exhausts by affecting fan power requirements and the balance of HVAC (heating, ventilating and air conditioning) systems. In addition, mechanical systems must respond to the wind flow patterns around buildings to avoid the reentry of exhausted pollutants into the building. This affects duct runs, vent positions, exhaust stack height, and stack exit velocity. Chapter 14 of the *ASHRAE Handbook of Fundamentals* discusses these issues in depth.[12]

Pollution Around Buildings. Pollutants emitted in the vicinity of buildings from traffic, parking garage ventilation exhausts, and building exhausts will be dispersed in patterns determined by the wind. Dispersal in the wake of single buildings has received fairly systematic study.[17,18] Although there have been numerous field and wind tunnel studies of dispersal from specific exhausts in specific built-up urban environments, such studies are difficult to generalize because of the variability of building configurations. Street canyons and courtyards sunk into a reasonably uniform rooftop line yield a typical airflow pattern under the influence of wind or of differential heating in the sunlight, as shown in Figure 10. Note that a south wind

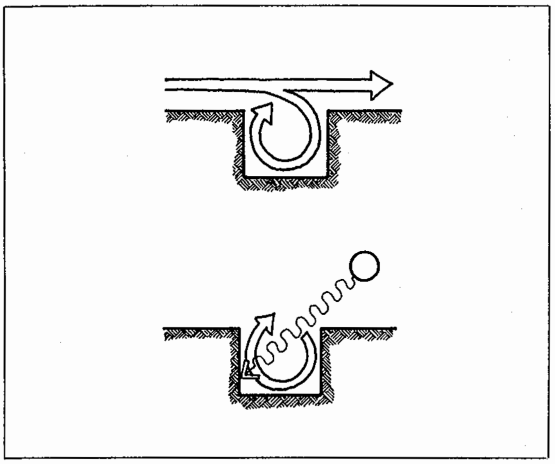

FIGURE 10. Typical airflow patterns in street canyons and courtyards under the influence of wind or differential heating by the sun.

will tend to suppress the roller set up by solar convection.

Using a model of an urban area, Figure 11 shows the wind influence on pollutant concentrations in some typical blocks.[19] This model shows that higher pollutant concentrations are experienced on the upwind side of the street.

Pedestrian Comfort. Strong winds around buildings may cause discomfort and even danger to pedestrians. People become discouraged with chronically windy open spaces, and by avoiding them they at least defeat the purpose of the open space, and at worst cause economic hardship to surrounding businesses. Pedestrian winds have been studied widely in recent years.[8,20] Figure 12

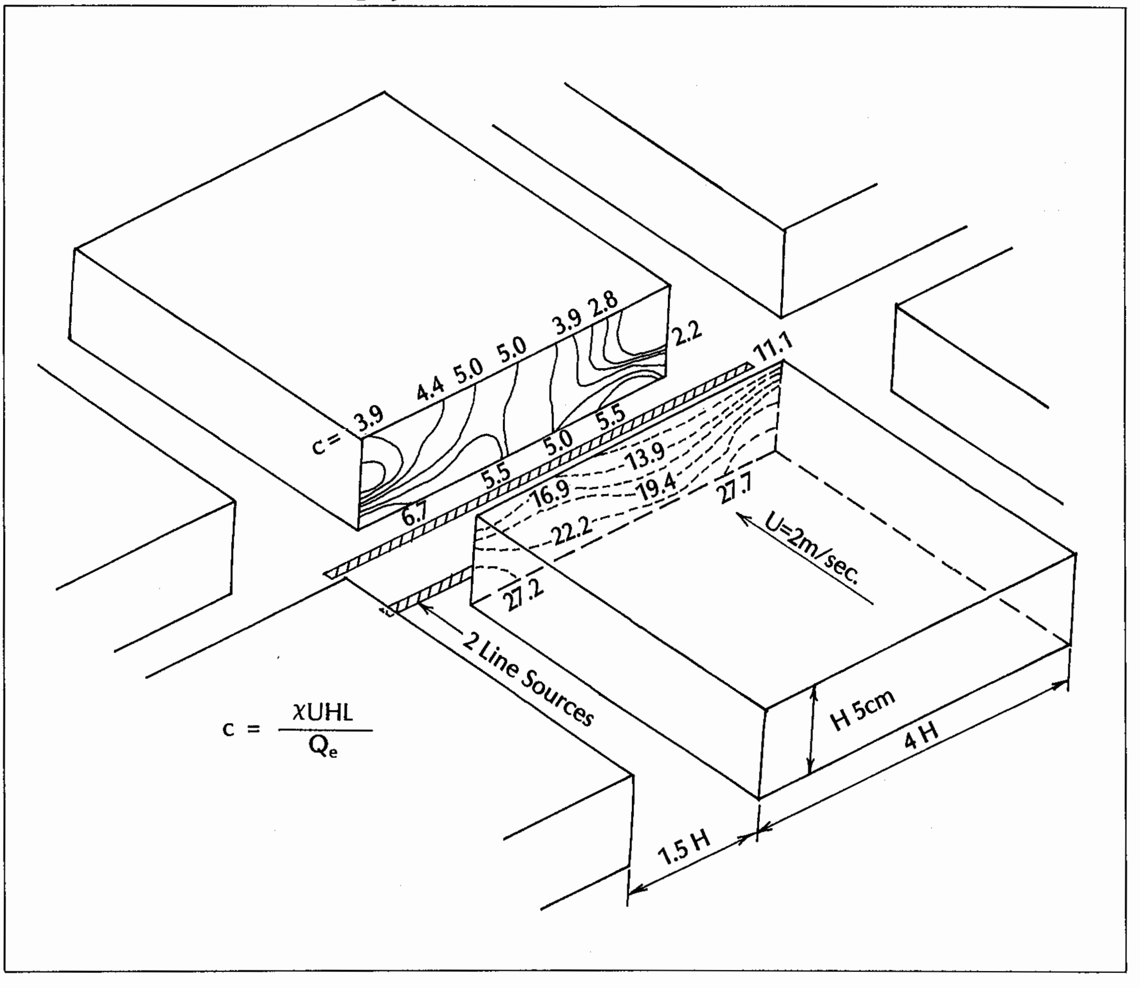

FIGURE 11. A model of wind influence on pollutant concentrations in some typical urban blocks.

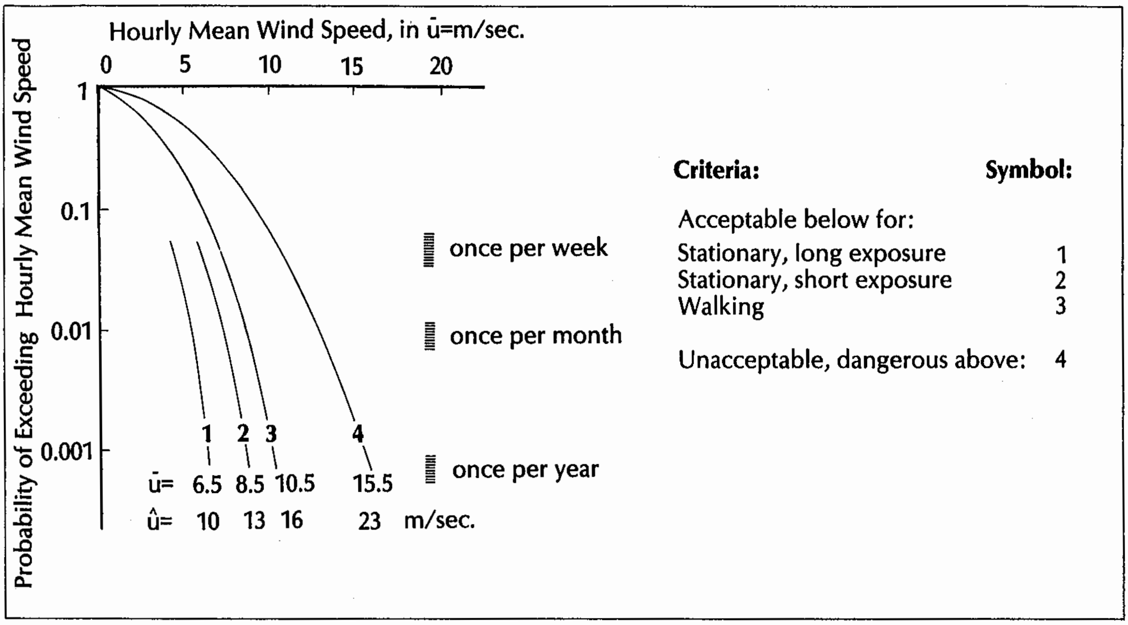

FIGURE 12. Acceptability criteria for pedestrian winds. The boldface numbers correspond to the symbols for acceptability criteria.

shows some pedestrian wind level acceptability criteria.[21] These criteria have been compared to the results of other researchers and been found to be consistent worldwide.[22] In the figure, $\bar{u}$ is the peak annual hourly mean, and $\hat{u}$ is the peak annual gust of a few seconds' duration.

Designers must evaluate the windiness of a site. For aerodynamically simple projects, it is possible to estimate windiness using previous experience. If this is not possible, a wind tunnel test of a model of the project is the only currently practical alternative. The velocity patterns obtained within the model are used to adjust the directional windspeed distributions from the most appropriate nearby weather station to obtain the wind climate on site. This information, when compared to the criteria shown in Figure 12, determines whether the site will have an acceptable outdoor wind environment.

Particle Transport. Wind may also influence a project by drifting particles of sand, soil or snow across circulation areas. There are even cases where winds generated around the base of tall beachfront hotels have scoured the beach away into the ocean. These problems may be controlled in the design of the buildings themselves, or by localized devices to trap particles.

Shelterbelts and artificial screens are commonly used to control snow and sand drifting (see Figure 8 on page 49). The optimum porosity for snow fences has been found to be around 50%, with no significant difference between vertical and horizontal slatting. There is no aerodynamic advantage to tilting the fence either into or away from the wind. Since there is considerable lateral transport around the ends of the fences, their length should be at least 30 times their height, and in staggered configurations. They should overlap by a length of at least 8 fence heights. Catchment efficiency of fences can be greatly increased by placement before a lee slope, or directly downwind of a rising slope.

Wind Records and Their Sources

Meteorological records are necessary to determine the local wind climate. Both the original data and their various summaries are kept at the National Climate Center (NCC) in Asheville, NC. Because most practitioners do not have the time or expertise to reduce the original data, summaries are useful.[23] The military SMOS and RUSSWO summaries are most comprehensive and are available for locations worldwide.[24] The *Airport Climatological Summary* provides useful information on wind frequency as a function of magnitude and direction.[25] Other summaries list extreme winds (fastest mile per hour) and other climatological variables. Most local libraries carry some of the climatological summaries. Copies are available from NCC at nominal cost.

Translation of meteorological conditions from an airport measurement site to a local site some distance away can be simple or quite involved. For example, wind speeds near the surface at a local site may differ from those at the nearest weather station due to different terrain roughness or other factors. In some cases, it may be desirable to monitor the wind over periods as short as a few days in order to make hour-by-hour comparisons with weather station values. In important projects, or where the climate changes rapidly over short distances, it is advisable to retain a consulting meteorologist.

Model Simulation

Modeling of wind effects on buildings and of wind flow and dispersion about buildings has been performed for more than two decades using boundary-layer wind tunnels. Comprehensive reviews of the techniques and similarity requirements are available.[26,27,28] In most cases, the modeling of atmospheric boundary layer winds requires the use of a wind tunnel in which the mean-velocity and turbulence characteristics of the wind flow are reproduced to scale. In other cases, particularly for dispersion problems, the thermal stability of the atmosphere should also be modeled. Within the wind tunnel, a model of the building or site requiring investigation must be constructed to a scale compatible with the modeled atmospheric flow. Instruments are placed in the model in order to obtain the information required — for example, in studies of pedestrian comfort, the magnitude of the horizontal wind and its fluctuations over time are typically measured by hot wire sensors at various ground level locations in the model. A model instrumented with pressure sensors to determine wind loads on a structure can also be scanned with a hot wire probe to determine pedestrian comfort in plazas or other areas around the building. In the model, the influence of surrounding buildings or topography should be included since they may have a major influence in the character of the wind flow at a particular point.

Conclusions

The influences of wind loads on building frames and cladding have been a traditional concern of engineers. Building designers have in recent years become markedly more aware of such influences, and there has been fairly widespread activity aimed at improving our ability to predict them in design. This increased awareness may seen in the construction of numerous boundary-layer wind tunnels in universities, research laboratories, and private consulting firms. Wind testing has become so sufficiently commonplace that it is used by architects and planners as well as engineers, with the result that influential early design decisions are now informed by wind considerations.

For the control of pedestrian-level winds, several cities have adopted codes requiring the testing of proposed building projects for their eventual wind climate. Researchers have developed fairly consistent acceptability criteria for wind effects on people, although there is still considerable room for improvement in this area.

Energy conservation concerns have prompted much recent research on natural ventilation, infiltration and mechanical system performance. Air pollution regulation has also fostered work on pollutant dispersion in the vicinity of buildings. As a result, a variety of new prediction methods have been developed for use by building designers.

Continued improvement is needed in estimating local climate statistics, and in the computer modeling of both the air flow itself and its influences on the built environment.

ACKNOWLEDGEMENTS — *Much of this article was originally published in the **Journal of Transportation Engineering**, Vol. 110, No. 5, September 1984, pp. 493-505, copyright 1984 ASCE,*

as a report to the Task Committee on Control of Microclimate Around Buildings, Committee on Aerodynamics, Aerospace Division, ASCE. The committee consisted of Edward Arens, chairman; Douglas Coonley; Hassan Nagib; and Jon Peterka.

EDWARD ARENS *is Associate Professor of Architecture at the University of California, Berkeley. He has degrees in architecture, forestry and city planning from Yale University and the University of Edinburgh. Since obtaining his Ph.D. in 1972, he has worked in private practice as a consultant on building climatology. He has also served as Chief of the Architectural Research Section at the National Bureau of Standards' Center for Building Technology, and is now in charge of the building science study area in the Department of Architecture.*

JON PETERKA *is Professor of Civil Engineering at Colorado State University. He received his bachelor's and master's degrees from Colorado State University and his Ph.D. from Brown University in 1968. His research interests include evaluating buildings for wind loads, the influence of adjacent buildings on wind loads, fluctuating wind pressures on structures, pedestrian discomfort due to wind, the characteristics of wake flow downstream of buildings and pollution dispersal. He is the current Chairman of the Aerodynamics Committee of the ASCE Aerospace Division and is a member of several ASCE committee task groups.*

REFERENCES

1. Geiger, R., *The Climate Near the Ground,* Cambridge, MA: Harvard University Press, 1965.

2. Bietry, J., Sacre, C., and Simiu, E., "Mean Wind Profiles and Changes of Terrain Roughness," *Journal of the Structural Division of the American Society of Civil Engineers,* Vol. 104, October 1978, pp. 1585-1593.

3. Smalley, C.L., *A Survey of Air Flow Patterns in the San Francisco Bay Region, 1952-1955,* San Francisco, CA: Bay Area Air Pollution Control District, undated.

4. Kittredge, J., *Forest Influences,* New York: McGraw Hill, 1948.

5. Beranek, W.J., and Van Koten, H., *Reducing Wind Discomfort Around Buildings,* Delft, Netherlands: Institute TNO for Building Materials and Building Structures, 1979, Part 1, Chapters 8-12 and Appendix.

6. Gandemer, J., "Wind Environment Around Buildings: Aerodynamic Concepts," *Proceedings of the Fourth International Conference on Wind Effects on Buildings and Structures,* London, England, 1975.

7. Gandemer, J., and Guyot, A., *Intégration du Phénomène Vent dans la Conception du Milieu Bâti,* Nantes, France: Centre Scientifique et Technique du Batiment, 1976.

8. Penwarden, A.D., and Wise, A.F.E., *Wind Environment Around Buildings,* London, England: Building Research Establishment, Her Majesty's Stationary Office, 1975.

9. Aynsley, R.M., "Effects of Airflow on Human Comfort," *Building Science,* Vol. 9, 1974, pp. 91-94.

10. Gandemer, J. and Guyot, A., *La Protection Contre le Vent,* Paris, France: Centre Scientifique et Technique du Batiment, 1981.

11. Givoni, B., *Man, Climate and Architecture,* New York: Van Nostrand Reinhold Company, 1981.

12. *American Society of Heating, Refrigerating, and Air Conditioning Engineers Transactions,*. New York: American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc., 1981.

13. Olgyay, V., *Design with Climate,* Princeton, NJ: Princeton University Press, 1963.

14. White, R.F., "Landscape Development and Natural Ventilation," *Landscape Architecture,* Vol. 45, No. 2, January 1955, pp. 72-81.

15. Sherman, M.H., and Grimsrud, D.T., "Infiltration-Pressurization Correlation: Simplified Physical Modeling," *American Society of Heating, Refrigerating, and Air Conditioning Engineers Transactions,* Vol. 86, Part 2, 1980.

16. Mattingly, G.E., and Peters, E.F., "Wind and Trees — Air Infiltration Effects on Energy in Housing," *Journal of Industrial Aerodynamics,* Vol. 2, No. 1, 1977, pp. 1-19.

17. Meroney, R.N., Peterka, J.A., and Kothari, K.M., "Wind Tunnel Measurements of Dispersion and Turbulence in the Wakes of Nuclear Reactor Plants," *NRC Report NUREG/CR-1475,* Nuclear Regulatory Commission, 1980.

18. Wilson, D.J., "Dilution of Exhaust Gases from Building Surface Vents," *American Society of Heating, Refrigerating, and Air Conditioning Engineers Transactions,* Vol. 83, 1977.

19. Cermak, J.E., Lombardi, D.J., and Thompson, R.S., *Applications of Physical Modeling to the Investigations of Air Pollution Problems in Urban Areas,* Report No. CEP 73-74-36, Fort Collins, CO: Fluid Dynamics and Diffusion Laboratory of Colorado State University, March 1974.

20. Isyumov, N., and Davenport, A.G., "The Ground Level Environment in Built-up Areas," *Proceedings of the Fourth International Conference on Wind Effects on Buildings and Structures,* Building Research Establishment, 1975, pp. 403-422.

21. Melbourne, W.H., "Criteria for Environmental Wind Conditions," *Journal of Industrial Aerodynamics,* Vol. 3, 1978, pp. 241-249.

22. Arens, E.A., "Designing for an Acceptable Wind Environment," *Transportation Engineering Journal of the American Society of Civil Engineers,* Vol. 107, No. TE2, March 1981, pp. 127-141.

23. Changery, M.J., Hodge, W.T., and Ramsdell, J.V., *Index-Summarized Wind Data,* Report BNWL-2220 Wind-11 UC-60, Asheville, NC.: National Climatic Center, 1977.

24. "Guide to Standard Weather Summaries and Climatic Services," *NAVAIR 50-1C-534,* Asheville, NC: National Climatic Center, January 1980.

25. *Climatology of the United States No. 90: Airport Climatological Summary,* Asheville, NC.: National Climatic Center, 1964-1974.

26. Cermak, J.E., "Laboratory Simulation of the Atmospheric Boundary Layer," *American Institute of Aeronautics and Astronautics Journal,* Vol. 9, 1971, pp. 1746-1754.

27. Cermak, J.E., "Application of Fluid Mechanics to Wind Engineering—A Freeman Scholar Lecture," *Journal of Fluids Engineering,* Vol. 97, pp. 9-38.

28. Reinhold, T., Ed., *Wind Tunnel Modeling for Civil Engineering Application: Proceedings of the International Workshop on Wind Tunnel Modeling Criteria and Techniques in Civil Engineering Applications, Gaithersburg, MD, USA, April 1982,* Cambridge, England: Cambridge University Press, 1982.

The following symbols are used in this article:

A = free area of inlet or outlet openings
C = factor for the effectiveness of the opening
c = mean concentration coefficient
H = building height
h = difference in height between inlet and outlet openings
L = reference length
n = flow exponent
Q = volumetric air flow
Q_* = pollutant emission rate
T = temperature
U_* = friction velocity
U_z = velocity at height z
V = wind velocity
z = height above ground surface
z_o = roughness length
ΔP = internal-external pressure difference
α = power law exponent
χ = mean concentration

Subscripts

i = inside
o = outside