CHAPTER 16

AIRFLOW AROUND BUILDINGS

AIRFLOW around buildings affects worker safety, process and building equipment operation, weather and pollution protection at inlets, and the ability to control environmental factors of temperature, humidity, air motion, and contaminants. Wind causes variable surface pressures on buildings that change intake and exhaust system flow rates, natural ventilation, infiltration and exfiltration, and interior pressures. The mean flow patterns and turbulence of wind passing over a building can cause recirculation of exhaust gases to air intakes. This chapter contains information for evaluating flow patterns, estimating wind pressures, and identifying problems caused by the effects of wind on intakes, exhausts, and equipment. Related information can be found in Chapters 12, 14, 26, and 27 of this volume; in Chapters 29, 30, 44, and 52 of the *ASHRAE Handbook—Applications*; and in Chapters 25, 30, and 36 of the *ASHRAE Handbook—Systems and Equipment*.

FLOW PATTERNS

Buildings having even moderately complex shapes, such as L- or U-shaped structures formed by two or three rectangular blocks, can generate flow patterns too complex to generalize for design. To determine flow conditions influenced by surrounding buildings or topography, wind tunnel or water channel tests of scale models or tests of existing buildings are required. However, if a building is oriented perpendicular to the wind, it can be considered as consisting of several independent rectangular blocks. Only isolated rectangular block buildings are discussed here. Saunders and Melbourne (1979), Hosker (1984, 1985), Walker et al. (1996), and English and Fricke (1997) review the effects of nearby buildings.

The **mean speed of wind** U_H approaching a building increases with height H above the ground (Figure 1). Both the upwind velocity profile shape and its turbulence intensity strongly influence flow patterns and surface pressures (Melbourne 1979). A **stagnation zone** exists on the upwind wall. The flow separates at the sharp edges to generate **recirculating flow zones** that cover the downwind surfaces of the building (roof, sides, and leeward walls) and extend for some distance into the **wake**. If the building has sufficient length L in the windward direction, the flow will reattach to the building (Figure 2) and may generate two distinct regions of separated recirculating flow—on the building and in its wake.

Surface flow patterns on the upwind wall are largely influenced by **approach wind characteristics**. Higher wind speed at roof level causes a larger **stagnation pressure** on the upper part of the wall than near the ground, which leads to downwash on the lower one-half to two-thirds of the building (Figure 1). On the upper one-quarter to one-third of the building, the surface flow is directed upward over the roof. For a building whose height H is three or more times the width W of the upwind face, an **intermediate zone** can exist between the **upwash** and **downwash** regions, where the **surface streamlines** pass horizontally around the building. The downwash on the lower surface of the upwind face separates from the building before it reaches ground level and moves upwind to form a **vortex** that can generate high velocities close to the ground. This **ground level upwind vortex** is carried around the sides of the building in a U shape (Figure 1) and is responsible for the suspension of dust and debris that can contaminate air intakes close to ground level.

For wind perpendicular to a building wall, the height H and width W of the upwind building face determine the flow patterns shown in Figure 2. According to Wilson (1979), the **scaling length** R is

$$R = B_s^{0.67} B_L^{0.33} \tag{1}$$

where

B_S = smaller of upwind building face dimensions H and W
B_L = larger of upwind building face dimensions H and W

When B_L is larger than $8B_S$, use $B_L = 8B_S$ in Equation (1). For buildings with varying roof levels or with wings separated by at least a distance B_S, only the height and width of the building face below the portion of the roof in question should be used to calculate R.

Streamline patterns are independent of wind speed and depend mainly on building shape and upwind conditions. Because of the three-dimensional flow around a building, the shape and size of the **recirculation airflow** is not constant over the surface. The airflow reattaches closer to the upwind building face along the edges of the building than it does near the middle of the roof and sidewalls (Figure 2). The height H_c of the **recirculation region** (Figures 1 and 3) also decreases near roof edges.

The wind above the roof recirculation region is affected by the presence of the building. The flow accelerates as the **streamlines** curve upward over the roof and decelerates as they curve downward over the wake on the downwind side of the building. The distance above roof level where a building influences the flow is approximately 1.5R (Figure 1). The roof pitch begins to affect flow when it exceeds about 15° (1:4). When roof pitch reaches 20° (1:3), the flow remains attached to the upwind pitched roof and produces a recirculation region downwind of the roof ridge that is larger than that for a flat roof.

The downwind wall of a building exhibits a region of low average velocity and high turbulence. Velocities near the downwind wall are typically one-quarter of those at the corresponding upwind wall location. Figures 1 through 3 show that an upward flow exists over most of the downwind walls. A flow recirculation region extends for an approximate distance L_r = 1.0R downwind.

If the angle of the approach wind is not perpendicular to the upwind face, complex flow patterns result. Strong vortices develop from the upwind edges of a roof, causing a strong downwash into the building wake above the roof. High speeds in these vortices cause large negative pressures near roof corners that can be a hazard to roof-mounted equipment during high winds. When the angle

The preparation of this chapter is assigned to TC 2.5, Air Flow Around Buildings.

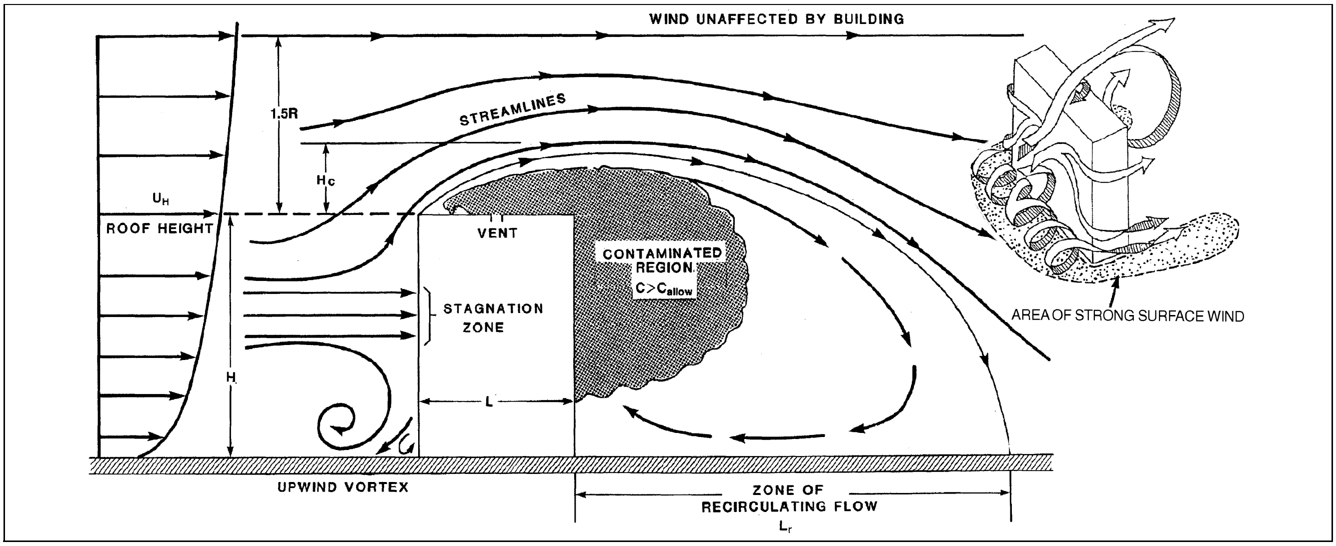

Fig. 1 Flow Patterns Around Rectangular Building

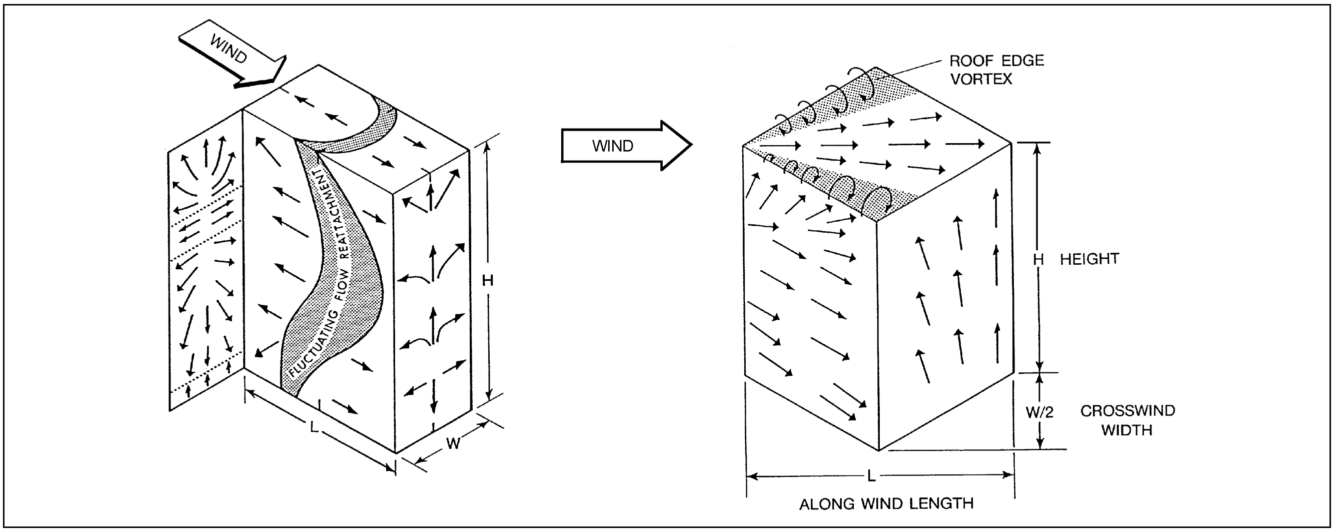

Fig. 2 Surface Flow Patterns and Building Dimensions

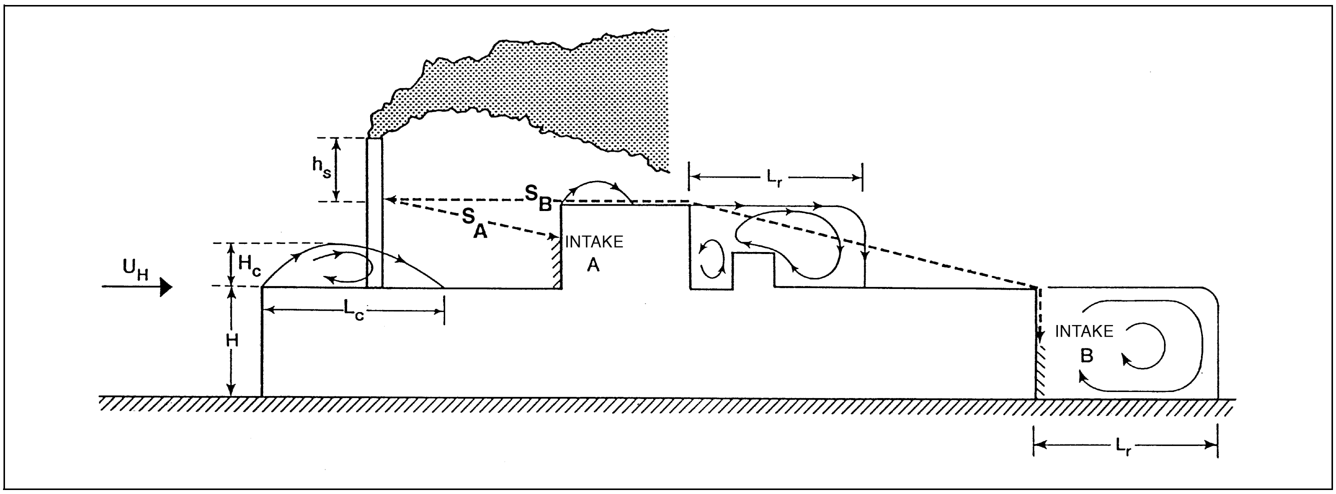

Fig. 3 Flow Recirculation Regions and Exhaust-to-Intake Stretched-String Distances
(Wilson 1982)

between the wind direction and the upwind face of the building is less than about 70°, the downwash-upwash patterns on the upwind face of the building are less pronounced, as is the ground level vortex shown in Figure 1. For an approach flow angle of 45°, streamlines remain close to the horizontal in their passage around the sides of the building (Figure 2), except near roof level where the flow is sucked upward into the roof edge vortices (Cochran 1992).

WIND PRESSURE ON BUILDINGS

In addition to the flow patterns described previously, the **turbulence** or **gustiness** of the approaching wind and the unsteady character of the separated flows cause surface pressures to fluctuate. The pressures discussed here are **time-averaged values**, with an averaging period of about 600 s. **Instantaneous pressures** may vary significantly above and below these averages, and **peak pressures** two or three times the mean values are possible. Although peak pressures are important with regard to structural loads, mean values are more appropriate for computing infiltration and ventilation rates. The time-averaged surface pressures are proportional to the wind velocity pressure p_v given by **Bernoulli's equation**:

$$p_v = \frac{\rho_a U_H^2}{2 g_c} \tag{2}$$

where

U_H = approach wind speed at upwind wall height H
ρ_a = ambient (outdoor) air density
g_c = gravitational proportionality constant

The difference p_s between the pressure on the building surface and the local **outdoor atmospheric pressure** at the same level in an undisturbed wind approaching the building is

$$p_s = C_p p_v \tag{3}$$

where C_p is the local wind pressure coefficient for the building surface.

The local wind speed U_H at the top of the wall that is required for Equation (2) is estimated by applying terrain and height corrections to the hourly wind speed U_{met} from a nearby meteorological station.

Table 1 Atmospheric Boundary Layer Parameters

Terrain Category	Description	Exponent a	Layer Thickness δ, ft
1	Large city centers, in which at least 50% of buildings are higher than 70 ft, over a distance of at least 0.5 mi or 10 times the height of the structure upwind, whichever is greater	0.33	1500
2	Urban and suburban areas, wooded areas, or other terrain with numerous closely spaced obstructions having the size of single-family dwellings or larger, over a distance of at least 0.5 mi or 10 times the height of the structure upwind, whichever is greater	0.22	1200
3	Open terrain with scattered obstructions having heights generally less than 30 ft, including flat open country typical of meteorological station surroundings	0.14	900
4	Flat, unobstructed areas exposed to wind flowing over water for at least 1 mi, over a distance of 1500 ft or 10 times the height of the structure inland, whichever is greater	0.10	700

U_{met} is generally measured in flat, open terrain. The anemometer that records U_{met} is located at a height H_{met}, usually 33 ft above ground level. The hourly average wind speed U_H at wall height H in the undisturbed wind approaching a building in its local terrain (Figures 1 and 3) can be calculated from U_{met} as follows:

$$U_H = U_{met}\left(\frac{\delta_{met}}{H_{met}}\right)^{a_{met}}\left(\frac{H}{\delta}\right)^{a} \tag{4}$$

The wind boundary layer thickness δ and exponent a for the local building terrain and a_{met} and δ_{met} for the meteorological station are determined from Table 1. Typical values for meteorological stations located in flat, open terrain (Category 3 in Table 1) are a_{met} = 0.14 and δ_{met} = 900 ft. The values and terrain categories in Table 1 are consistent with those adopted in other engineering applications, for example ASCE *Standard* 7. Equation (4) gives the wind speed at height H above the average height of local obstacles, such as buildings and vegetation, weighted by the plan-area. At heights at or below this average obstacle height (e.g., at roof height in densely built-up suburbs), the speed depends on the geometrical arrangement of the buildings, and Equation (4) is less reliable.

An alternative mathematical description of the **atmospheric boundary layer**, which uses a logarithmic function, is given by Deaves and Harris (1978). While this model is more complicated than the power law used in Equation (4), it more closely models the real physics of the atmosphere and has been adopted by several foreign codes (e.g., SAA *Standard* AS-1170 from Australia).

Local Wind Pressure Coefficients

Values of the mean local wind pressure coefficient C_p used in Equation (3) depend on building shape, wind direction, and the influence of nearby buildings, vegetation, and terrain features. Accurate determination of C_p can be obtained only from wind tunnel model tests of the specific site and building. Ventilation rate calculations for single, unshielded rectangular buildings can be reasonably estimated using existing wind tunnel data. Many wind load codes (e.g., ASCE 7-98, AS-1170) give mean pressure coefficients for common building shapes.

Figure 4 shows pressure coefficients for walls of a tall rectangular cross section building (high-rise) sited in urban terrain (Davenport and Hui 1982). Figure 5 shows pressure coefficients for walls of a low-rise building (Holmes 1986). Generally, high-rise buildings are those where the height H is more than three times the cross-wind width W. For $H > 3W$, use Figure 4, and for $H < 3W$, use Figure 5. At a wind angle $\theta = 0°$ (e.g., wind perpendicular to the face in question), the pressure coefficients are positive, and their magnitudes decrease near the sides and the top as the flow velocities increase.

As can be seen in Figure 4, C_p generally increases with height, which reflects the increasing velocity pressure in the approach flow as wind speed increases with height. As the wind direction moves off normal ($\theta = 0°$), the region of maximum pressure occurs closer to the upwind edge (B in Figure 4) of the building. At a wind angle of $\theta = 45°$, the pressures become negative at the downwind edge (A in Figure 4) of the front face. At some angle θ between 60° and 75°, the pressures become negative over the whole front face. For θ = 90°, maximum suction (negative) pressure occurs near the upwind edge (B in Figure 4) of the building side and then recovers towards $C_p = 0$ towards the downwind edge (A in Figure 4). The degree of this recovery depends on the length of the side in relation to the width W of the structure. For wind angles larger than $\theta = 100°$, the side is completely within the separated flow of the wake and the spatial variations in pressure over the face are not as great. The average pressure on a face is positive for wind angles from $\theta = 0°$ to almost 60° and negative (suction) for $\theta = 60°$ to 180°.

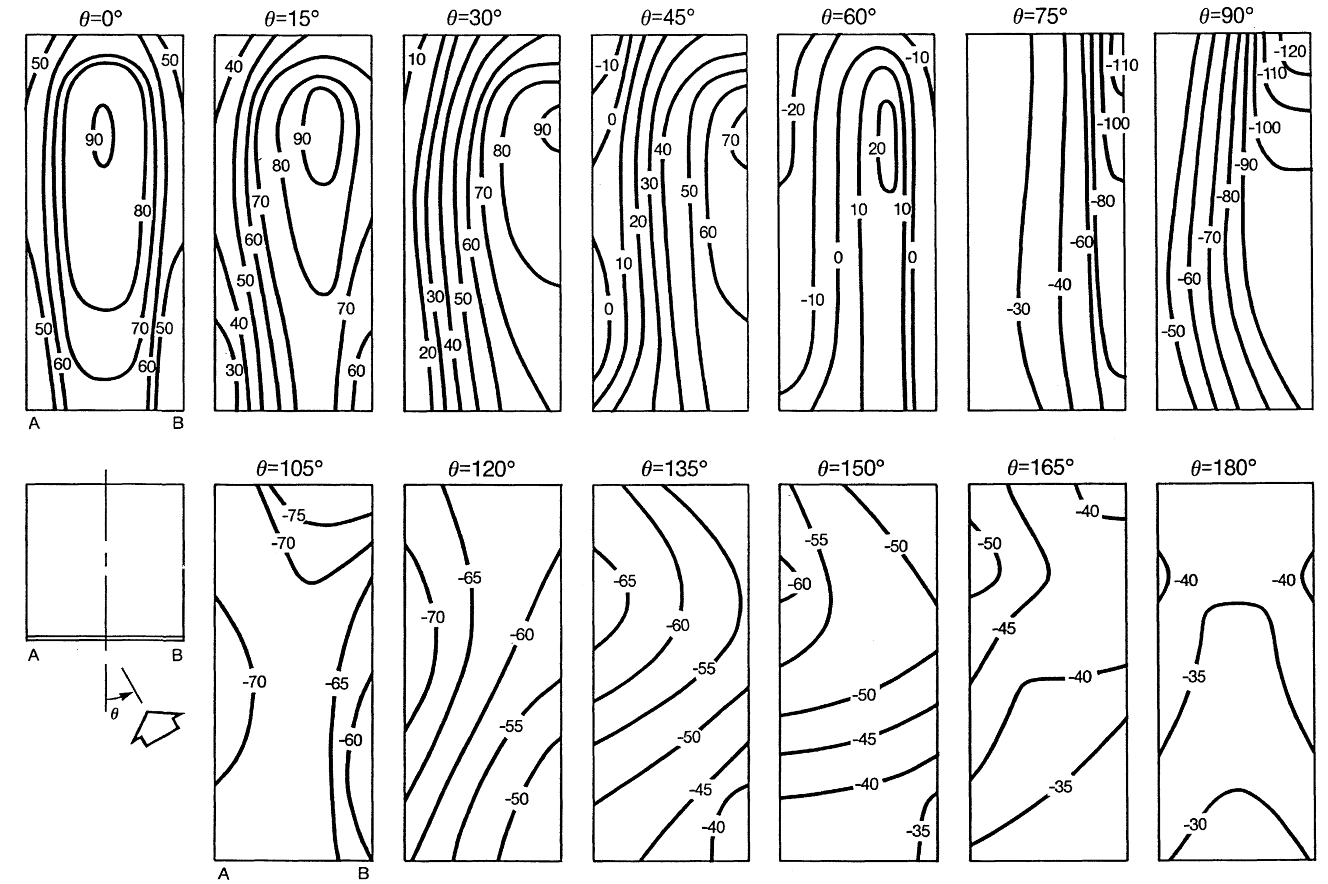

Fig. 4 Local Pressure Coefficients ($C_p \times 100$) for Tall Building with Varying Wind Direction
(Davenport and Hui 1982)

A similar pattern of behavior in the wall pressure coefficients for a low-rise building is shown in Figure 5. Here, the recovery from the strong suction with distance from the upwind edge is more rapid.

Surface Averaged Wall Pressures

Surface averaged pressure coefficients may be used in determining ventilation and/or infiltration rates, as discussed in Chapter 26. Figure 6 shows the surface pressure coefficient C_s averaged over a complete wall of a low-rise building (Swami and Chandra 1987). The figure also includes the values calculated from the pressure distributions shown in Figure 5. Similar results for a tall building are shown in Figure 7 (Akins et al. 1979).

The wind-induced indoor-outdoor pressure difference is found using the coefficient $C_{p\,(in\text{-}out)}$, which is defined as

$$C_{p(in\text{-}out)} = C_p - C_{in} \qquad (5)$$

where C_{in} is the internal wind-induced pressure coefficient. For uniformly distributed air leakage sites in all the walls, C_{in} is about −0.2.

Roof Pressures

Surface pressures on the roof of a low-rise building depend strongly on roof slope. Figure 8 shows typical distributions for a wind direction normal to a side of the building. For very low slopes, the pressures are negative over the whole roof surface. The magnitude is greatest within the separated flow zone near the leading edge and recovers toward the free stream pressure downwind of the edge. For steeper slopes, the pressures are weakly positive on the windward slope and negative within the separated flow over the leeward slope. With a wind angle of about 45°, the vortices originating at the leading corner of a roof with a low slope can induce very large localized negative pressures (Figure 2). A similar vortex forms on the downwind side of a leading ridge end on a steep roof. A discussion of roof corner vortices and how to disrupt their influence may be found in Cochran and Cermak (1992) and Cochran and English (1997), respectively. Figure 9 shows the average pressure coefficient over the roof of a tall building (Akins et al. 1979).

The section on Combining Driving Forces in Chapter 26 discusses the effect of stack pressure and mechanical systems on infiltration and ventilation in a building.

Interference and Shielding Effects on Pressures

Nearby structures strongly influence surface pressures on both high- and low-rise buildings. These effects are very strong for spacing-to-height ratios less than five, where the distributions of pressure shown in Figures 4 through 9 do not apply. Although the effect of shielding is for low-rise buildings still significant at larger spacing, it is largely accounted for by the reduction in p_v with increased terrain roughness. Saunders and Melbourne (1979), Sherman and Grimsrud (1980), Bailey and Kwok (1985), and Walker et al. (1996) discuss interference. English and Fricke (1997) discuss shielding through use of an interference index, while Walker et al. (1996) present a wind shadow model for predicting shelter factors. Chapter 26 gives shielding classes for air infiltration and ventilation applications.

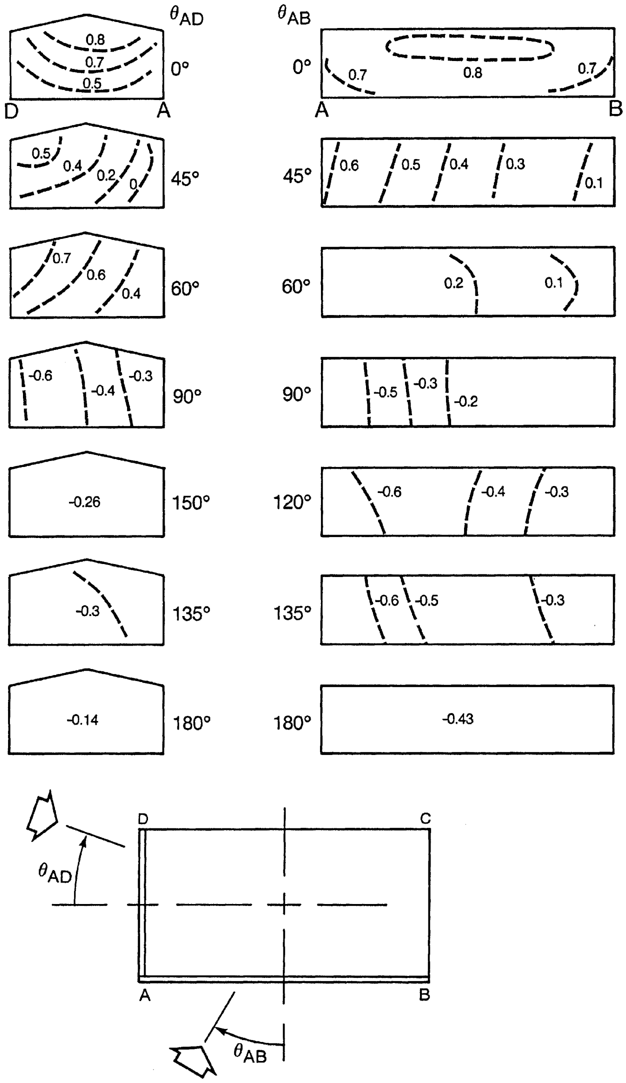

Fig. 5 Local Pressure Coefficients for Walls of Low-Rise Building with Varying Wind Direction
(Holmes 1986)

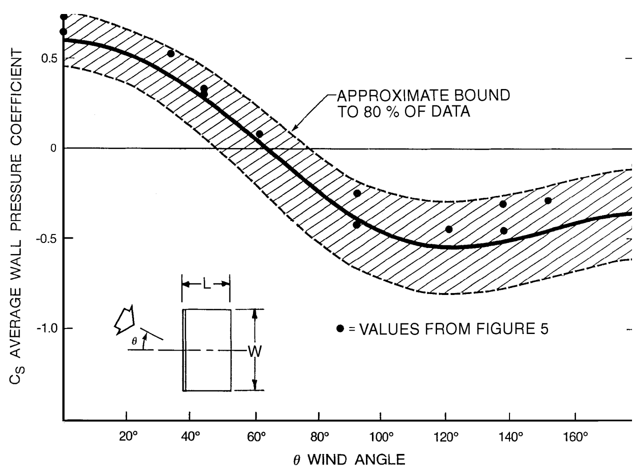

Fig. 6 Variation of Surface Averaged Wall Pressure Coefficients for Low-Rise Buildings
(Swami and Chandra 1987)

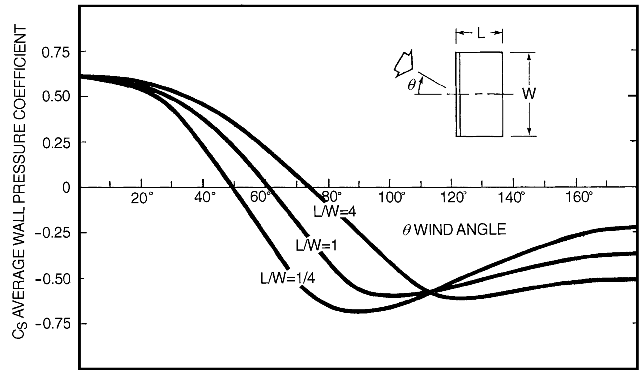

Fig. 7 Surface Averaged Wall Pressure Coefficients for Tall Buildings
(Akins et al. 1979)

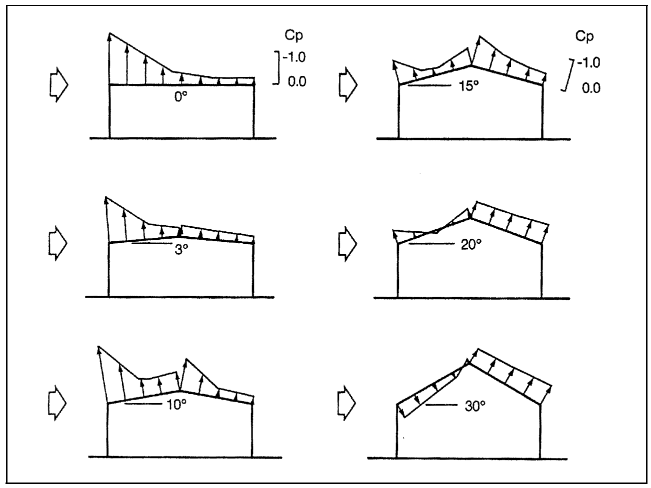

Fig. 8 Local Roof Pressure Coefficients for Roof of Low-Rise Buildings
(Holmes 1986)

Sources of Wind Data

In order to design for the effects of airflow around buildings, wind speed and direction frequency data should be obtained. The simplest forms of wind data are tables or charts of climatic normals, which give hourly average wind speeds, prevailing wind directions, and peak gust wind speeds for each month of the year. This information can be found in sources such as The *Weather Almanac* (Bair 1992) and the *Climatic Atlas of the United States* (DOC 1968). Climatic design information, including wind speed at various frequencies of occurrence, is included in Chapter 27. A current source, which contains information on wind speed and direction frequencies, is the *International Station Meteorological Climatic Summary* available in CD-ROM format from the National Climatic Data Center (NCDC) in Asheville, North Carolina. Where more detailed information is required, digital records of hourly winds and other meteorological parameters are available (on magnetic tape or CD-ROM) from the NCDC for stations throughout the world. Most countries also have weather services that provide data. For example, in Canada, the Atmospheric Environment Service in Downsview, Ontario, provides hourly meteorological data and summaries.

When an hourly wind speed U_{met} at a specified probability level (e.g., the wind speed that is exceeded 1% of the time) is desired, but only the average annual wind speed U_{annual} is available for a given meteorological station, U_{met} may be estimated from Table 2. The

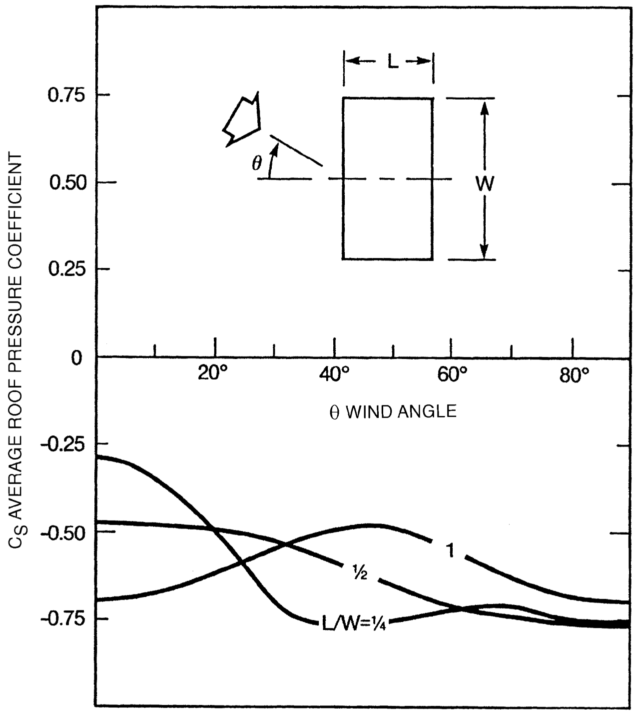

Fig. 9 Surface Averaged Roof Pressure Coefficients for Tall Buildings
(Akins et al. 1979)

Table 2 Typical Relationship of Hourly Wind Speed U_{met} to Annual Average Wind Speed U_{annual}

Percentage of Hourly Values That Exceed U_{met}	Wind Speed Ratio U_{met}/U_{annual}
90%	0.2 ± 0.1
75%	0.5 ± 0.1
50%	0.8 ± 0.1
25%	1.2 ± 0.15
10%	1.6 ± 0.2
5%	1.9 ± 0.3
1%	2.5 ± 0.4

ratios U_{met}/U_{annual} are based on long-term data from 24 weather stations widely distributed over North America. At these stations, U_{met} ranges from 7 to 14 mph. The uncertainty ranges listed in Table 2 are one standard deviation of the wind speed ratios. The following example demonstrates the use of Table 2.

Example 1. The wind speed U_{met} that is exceeded 1% of the time (88 hours per year) is needed for a building pressure or exhaust dilution calculation. If U_{annual} = 9 mph, find U_{met}.

Solution: From Table 2, the wind speed U_{met} exceeded 1% of the time is 2.5 ± 0.4 times U_{annual}. For U_{annual} = 9 mph, U_{met} is 23 mph with an uncertainty range of 19 to 26 mph at one standard deviation.

Using a single prevailing wind direction for design can cause serious errors. For any set of wind direction frequencies, one direction always has a somewhat higher frequency of occurrence. Thus, it is often called the prevailing wind, even though winds from other directions may be almost as frequent.

When using long-term meteorological records, check the anemometer location history as the instrument may have been relocated and its height varied. This can affect its directional exposure and the recorded wind speeds. Equation (4) can be used to correct wind data

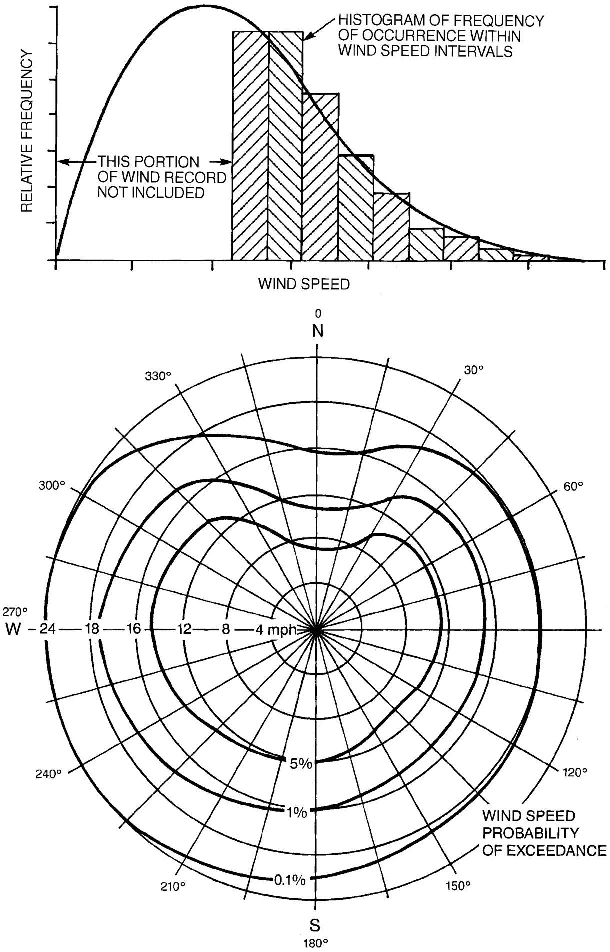

Fig. 10 Frequency Distribution of Wind Speed and Direction

collected at different mounting heights. Poor anemometer exposure due to obstructions or mounting on top of a building cannot be easily corrected, and the records for that period should be deleted.

If an estimate of the probability of an extreme wind speed outside the range of the recorded values at a site is required, the observations may be fit to an appropriate probability distribution (e.g., a Weibull distribution) and the particular probabilities calculated from the resulting function (see Figure 10). This process is usually repeated for each of 16 wind directions (e.g., 22.5° intervals).

Where estimates at extremely low probability (high wind speed) are required, curve fitting at the tail of the probability distribution is very important and may require special statistical techniques applicable to extreme values (see Chapter 27). Building codes for wind loading on structures contain information on estimating extreme wind conditions. For ventilation applications, extreme winds are usually not required, and the 99 percentile limit can be accurately estimated from airport data averaged over less than 10 years.

Estimating Wind at Sites Remote from Recording Stations

Many building sites are located far from the nearest long-term wind recording site, which is usually an airport meteorological station. To estimate wind conditions at such sites, the terrain surrounding both the anemometer site and the building site should be checked. In the simplest case of flat or slightly undulating terrain with few obstructions extending for large distances around and between the anemometer site and building site, recorded wind data can be assumed to be representative of that at the building site. Wind direction occurrence frequency at a building site should be inferred from airport data only if the two locations are on the same terrain, with no terrain features that could alter wind direction between them.

In cases where the only significant difference between the anemometer site terrain and the building site terrain is surface roughness, the mean wind speed can be adjusted using Equation (4) and Table 1, to yield approximate wind velocities at the building site. Wind direction frequencies at the site are assumed to be the same as at the recording station.

In using Equation (4), cases may be encountered where, for a given wind direction, the terrain upwind of either the building site or the recording site does not fall into just one of the categories in Table 1. The terrain immediately upwind of the site may fall into one category, while that somewhat further upwind falls into a different category. For example, at a downtown airport the terrain may be flat and open (Category 3) immediately around the recording instrument, but urban or suburban (Category 2) a relatively short distance away. This difference in terrains also occurs when a building site or recording site is in an urban area near open water or at the edge of town. In these cases, the suggested approach is to use the terrain category that is most representative of the average condition within approximately 1 mile upwind of the site (Deaves 1981). If the average condition is somewhere between two categories described in Table 1, the values of a and δ can be interpolated from those given in the table.

A rough guideline is that only wind speeds U_H of 9 mph or greater at the building site can be estimated reliably using Equation (4) and Table 2 for building and meteorological stations in different terrain categories.

In addition to changes in **surface roughness**, several other factors are important in causing the wind speed and direction at a building site to differ from values recorded at a nearby meteorological station. Wind speeds for buildings on hillcrests or in valleys where the wind is accelerated or channeled can be 1.5 times higher than meteorological station data. Wind speeds for buildings sheltered in the lee of hills and escarpments can be reduced to 0.5 times the values at nearby flat meteorological station terrain.

Solar heating of valley slopes can cause light winds of 2 to 9 mph to occur as warm air flows upslope. At night, radiant cooling of the ground can produce similar speeds as cold air drains downslope. In general, rolling terrain experiences a smaller fraction of low speeds than nearly flat terrain.

When the wind is calm or light in the rural area surrounding a city, urban air tends to rise in a buoyant plume over the city center. This rising air, heated by man-made sources and higher solar absorption in the city, is replaced by air pushed toward the city center from the edges. In this way, the **urban heat island** can produce light wind speeds and direction frequencies significantly different than those at a rural meteorological station.

In more **complex terrain**, both wind speed and direction may be significantly different from those at the distant recording site. In these cases, building site wind conditions should not be estimated from airport data. Options are either to establish an on-site wind recording station or to commission a detailed wind tunnel correlation study between the building site and long-term meteorological station wind observations.

WIND EFFECTS ON SYSTEM OPERATION

With few exceptions, building intakes and exhausts cannot be located or oriented such that a prevailing wind ensures ventilation and air-conditioning system operation. Wind can assist or hinder inlet and exhaust fans, depending on their positions on the building, but even in locations with a predominant wind direction, the ventilating system must perform adequately for all other directions. To

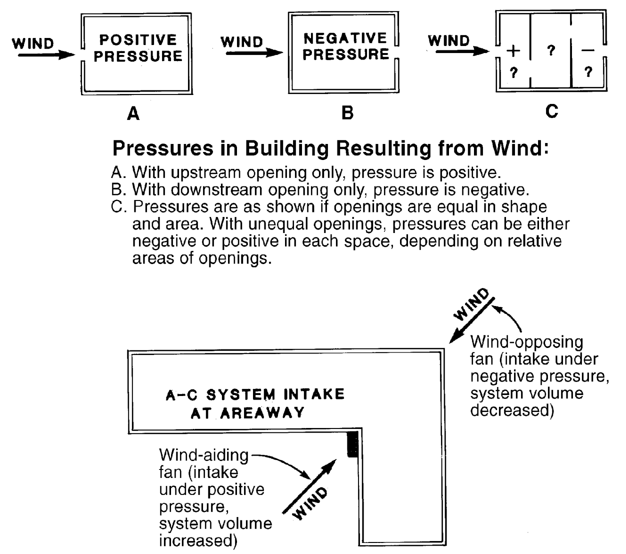

Fig. 11 Sensitivity of System Volume to Locations of Building Openings, Intakes, and Exhausts

avoid variability in system flow rates, use Figures 4, 5, and 8 as a guide to placing inlets and exhausts in locations where the surface pressure coefficients do not vary greatly with the wind direction.

Cooling towers and similar equipment should be oriented to take advantage of prevailing wind directions, based on careful study of the meteorological data and flow patterns on the building for the area and time of year involved.

A building with only upwind openings is under a positive pressure (Figure 11). Building pressures are negative when there are only downwind openings. A building with internal partitions and openings is under various pressures depending on the relative sizes of the openings and the wind direction. With larger openings on the windward face, the building interior tends to remain under positive pressure; the reverse is also true (see Figures 4 through 9, and Chapter 26).

Airflow through a wall opening results from differential pressures, which may exceed 0.5 in. of water during high winds. Supply and exhaust systems, openings, dampers, louvers, doors, and windows make the building flow conditions too complex for direct calculation. Iterative calculations are required because of the nonlinear dependence of volume flow rate on the differential pressure across an opening. Several **multizone airflow models** are available for these iterative calculations (Walton 1997, Feustel and Dieris 1992). The opening and closing of doors and windows by building occupants add further complications. In determining $C_{p(in\text{-}out)}$ from Equation (5), the wind direction is more important than the position of an opening on a wall, as shown in Figures 4 and 5. Please see Chapter 26 for more detailed information regarding wind effects on building ventilation, including natural and mechanical systems.

Natural and Mechanical Ventilation

With **natural ventilation**, wind may augment, impede, or sometimes reverse the airflow through a building. For large roof areas (Figure 2), the wind can reattach to the roof downwind of the leading edge. Thus, any natural ventilation openings could see either a positive or negative pressure, dependent on wind speed and wind direction. Positive pressure existing where negative pressures were expected could lead to a reversal of expected natural ventilation. These reversals can be avoided by using stacks, continuous roof ventilators, or other exhaust devices in which the flow is augmented by the wind.

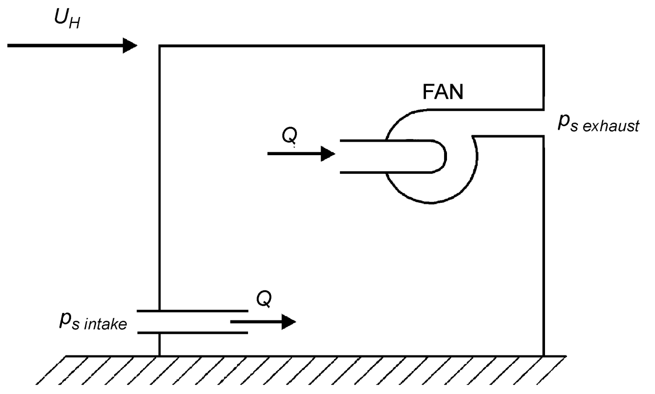

Fig. 12 Intake and Exhaust Pressures on Exhaust Fan in Single Zone Building

Mechanical ventilation is also affected by wind conditions. A low-pressure wall exhaust fan (0.05 to 0.1 in. of water) can suffer drastic reduction in capacity. Flow can be reversed by wind pressures on windward walls, or its rate can be increased substantially when subjected to negative pressures on the lee and other sides. Clarke (1967), when measuring medium-pressure air-conditioning systems (1 to 1.5 in. of water), found flow rate changes of 25% for wind blowing into intakes on an L-shaped building compared to wind blowing away from intakes. Such changes in flow rate can cause noise at the supply outlets and drafts in the space served.

For mechanical systems, the wind can be thought of as an additional pressure source in series with a system fan, either assisting or opposing it (Houlihan 1965). Where system stability is essential, the supply and exhaust systems must be designed for high pressures (about 3 to 4 in. of water) or must use devices to actively minimize unacceptable variations in flow rate. To conserve energy, the system pressure selected should be consistent with system needs.

Quantitative estimates of the effect of wind on a mechanical ventilation system can be made by using the pressure coefficients in Figures 4 through 9 to calculate the wind pressure on air intakes and exhausts. A simple worst-case estimate is to assume a system with 100% makeup air supplied by a single intake and exhausted from a single outlet. The building is treated as a single zone, with an exhaust-only fan as shown in Figure 12. This will overestimate the effect of wind on system volume flow.

Combining Equations (2) and (3), the wind pressures at the air intake and exhaust locations are

$$p_{s\ intake} = C_{p\ intake}\frac{\rho_a U_h^2}{2g_c} \quad (6)$$

$$p_{s\ exhaust} = C_{p\ exhaust}\frac{\rho_a U_h^2}{2g_c} \quad (7)$$

For the single zone building shown in Figure 12, a worst-case estimate of wind effect neglects any flow resistance in the intake grill and duct, making the interior building pressure $p_{interior}$ equal to the outdoor wind pressure on the intake, $p_{interior} = p_{s\ intake}$. Then, with all the system flow resistance assigned to the exhaust duct in Figure 12, and a pressure rise Δp_{fan} across the fan, the pressure drop from outdoor intake to outdoor exhaust yields

$$(p_{s\ intake} - p_{s\ exhaust}) + \Delta p_{fan} = F_{sys}\frac{\rho Q^2}{A_L^2 g_c} \quad (8)$$

where F_{sys} is the system flow resistance, A_L is the flow leakage area, and Q is the system volume flow rate. This result shows that for the worst case estimate, the wind induced pressure difference simply adds to or subtracts from the fan pressure rise. With the inlet and exhaust pressures from Equations (6) and (7), the effective fan pressure rise $\Delta p_{fan\ eff}$ is

$$\Delta p_{fan\ eff} = \Delta p_{fan} + \Delta p_{wind} \quad (9)$$

where $$\Delta p_{wind} = (C_{p\ intake} - C_{p\ exhaust})\frac{\rho_a U_h^2}{2g_c} \quad (10)$$

The fan will be wind-assisted when $C_{p\ intake} > C_{p\ exhaust}$ and wind-opposed when the wind direction changes causing $C_{p\ intake} < C_{p\ exhaust}$. The effect of wind-assisted and wind-opposed pressure differences is illustrated in Figure 13.

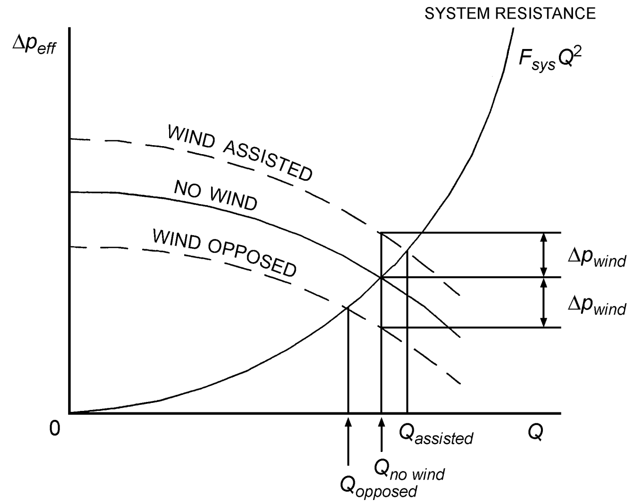

Fig. 13 Effect of Wind-Assisted and Wind-Opposed Flow

Example 2. Make a worst-case estimate for the effect of wind on the supply fan for a low-rise building with a height H = 50 ft located in a city suburb. Use the hourly average wind speed that will be exceeded only 1% of the time and assume an annual hourly average speed of U_{annual} = 8 mph measured on a meteorological tower at height H_{met} = 33 ft at a nearby airport. Outdoor air density is ρ_a = 0.075 lb_m/ft^3.

Solution: From Table 2 the wind speed that is exceeded only 1% of the hours each year will be a factor of 2.5 ± 0.4 higher than the annual average of 8 mph, so the 1% maximum speed at the airport meteorological station is

$$U_{met} = 2.5 \times 8 = 20 \text{ mph}$$

From Table 1, the airport meteorological station is in terrain category 3, with a boundary layer thickness δ_{met} = 900 ft and a velocity profile exponent a = 0.14. The suburban location of the building places it in terrain category 2 in Table 2, with δ = 1200 ft and a = 0.22. Using Equation (4) to determine the wind speed U_H at roof level H = 50 ft in the flow approaching the building,

$$U_H = 20\left(\frac{900}{33}\right)^{0.14}\left(\frac{50}{1200}\right)^{0.22} = 15.8 \text{ mph} = 23.2 \text{ ft/s}$$

A worst-case estimate of wind effect must assume intake and exhaust locations on the building that produce the largest difference ($C_{p\ intake} - C_{p\ exhaust}$) in Equations (9) and (10). From Figure 5, the largest difference occurs for the intake on the upwind wall AB and the exhaust on the downwind wall CD, with a wind angle θ_{AB} = 0°. For this worst case, $C_{p\ intake}$ = +0.8 on the upwind wall and $C_{p\ exhaust}$ = –0.43 on the downwind wall. Using these coefficients in Equations (9) and (10) to evaluate the effective fan pressure $\Delta p_{fan\ eff}$,

$$\Delta p_{fan\ eff} = \Delta p_{fan} + [0.8 - (-0.43)]\frac{0.075(23.2)^2}{2(32.2)}$$

$$= \Delta p_{fan} + 0.77\,\text{lb}_f/\text{ft}^2$$

Expressing this as in. of water pressure for water density of 62.4 lb_m/ft^3 and gravitational acceleration of 32.2 ft/s^2,

$$\Delta p_{wind} = \frac{0.77 \times 32.2}{62.4 \times 32.2} = 0.012\ \text{ft} = 0.15\ \text{in. of water}$$

This wind-assisted hourly averaged pressure is exceeded only 1% of the time (88 hours per year). When the wind direction reverses, the outlet will be on the upwind wall and the inlet on the downwind wall, producing wind-opposed flow, changing the sign from +0.15 to –0.15 in of water. The importance of these pressures depends on their size relative to the fan pressure rise Δp_{fan}, as shown in Figure 13.

Building Pressure Balance

Proper **building pressure balance** avoids flow conditions that make doors hard to open, cause drafts, and prevent the confinement of contaminants to specific areas. Although the supply and exhaust systems in an area may be in nominal balance, wind can upset this balance, not only because of the changes in fan capacity but also by superimposing infiltrated or exfiltrated air or both on the area. These effects can make it impossible to control environmental conditions. Where building balance and minimum infiltration are important, consider the following:

- Design HVAC system with pressure adequate to minimize wind effects
- Include controls to regulate flow rate or pressure or both
- Separate supply and exhaust systems to serve each building area requiring control or balance
- Effect of doors (possibly self-closing) or double-door air locks to noncontrolled adjacent areas, particularly outside doors
- Sealing of windows and other leakage sources and closing natural ventilation openings.

System volume and pressure control is described in Chapter 46 of the *ASHRAE Handbook—Applications*. This control is not possible without adequate system pressure for both the supply and exhaust systems to overcome wind effects. Such a control system may require fan inlet or discharge dampers, fan speed or pitch control, or both.

Fume Hood Operation

Wind effects can interfere with safe fume hood operation. Supply volume variations can cause both disturbances at hood faces and a lack of adequate fume hood makeup air. Volume surges, due to fluctuating wind pressures acting on the exhaust system, can cause momentary inadequate hood exhaust. If highly toxic contaminants are involved, surging is unacceptable. The system should be designed to eliminate this condition. On low-pressure exhaust systems, it is impossible to test the hoods under wind-induced, surging conditions. These systems should be tested during calm conditions for safe flow into the hood faces; they should be rechecked by smoke tests during high wind conditions. For more information, see Chapter 14 of the *ASHRAE Handbook—Applications*.

Minimizing Wind Effect on System Volume

Wind effect can be reduced by careful selection of inlet and exhaust locations. Because wall surfaces are subject to a wide variety of positive and negative pressures, wall openings should be avoided when possible. When they are required, wall openings should be away from corners formed by building wings (Figure 11). Mechanical ventilation systems should operate at a pressure high enough to minimize wind effect. **Low-pressure systems** and **propeller exhaust fans** should not be used with wall openings unless their ventilation rates are small or they are used in noncritical services such as storage areas.

Although roof air intakes in flow recirculation zones best minimize wind effect on system flow rates, current and future air quality in these zones must be considered. These locations should be avoided if a source of contamination exists or may be added in the future. The best area is near the middle of the roof because the negative pressure there is small and least affected by changes in wind direction (Figure 8). Avoid the edges of the roof and walls, where large pressure fluctuations occur. Either vertical or horizontal (mushroom) openings can be used. On roofs having large areas, where the intake may be outside the roof recirculation zone, mushroom or 180° gooseneck designs minimize impact pressure from wind flow. The 135° gooseneck that is frequently used or vertical louvered openings are undesirable for this purpose or for rain protection.

Heated air or contaminants should be exhausted vertically through stacks, above the roof recirculation zone. Horizontal, louvered (45° down), and 135° gooseneck discharges are undesirable, even for heat removal systems, because of their sensitivity to wind effects. A 180° gooseneck for systems handling hot air may be undesirable because of air impingement on tar and felt roofs. Vertically discharging stacks located in a recirculation region (except near a wall) have the advantage of being subjected only to negative pressure created by wind flow over the tip of the stack. See Chapter 44 of the *ASHRAE Handbook—Applications* for information regarding stack design.

BUILDING INTERNAL PRESSURE AND FLOW CONTROL

In air-conditioning and ventilation systems for a building containing airborne contaminants, the correct internal airflow is toward the contaminated areas. Airflow direction is maintained by controlling pressure differentials between spaces. In a laboratory building, for example, peripheral rooms such as offices and conference rooms are maintained at a positive pressure, and laboratories at a negative pressure, both with reference to corridor pressure. Pressure differentials between spaces are normally obtained by balancing the air-conditioning and ventilation supply system airflows in the spaces in conjunction with the exhaust systems in the laboratories, with differential pressure instrumentation to control the airflow. Chapter 46 of the *ASHRAE Handbook—Applications* has further information on controls.

Airflow in corridors is sometimes controlled by an outdoor reference probe that senses static pressure at doorways and air intakes. The differential pressure measured between the corridor and the outside may then signal a controller to increase or decrease airflow to the corridor. Unfortunately, it is difficult to locate an external probe where it will sense the proper external static pressure. High wind velocity and resulting pressure changes around entrances can cause great variations in pressure. Care must be taken to ensure that the probe is unaffected by wind pressure.

The pressure differential for a room adjacent to a corridor can be controlled using the corridor pressure as the reference. Outdoor pressure cannot control pressure differentials within rooms, even during periods of relatively constant wind velocity (wind-induced pressure). A single pressure sensor can measure the outside pressure at one point only and may not be representative of pressures elsewhere.

SCALE MODEL SIMULATION AND TESTING

For many routine design applications, the flow patterns and wind pressures can be estimated using the data and equations presented in the previous sections. Exhaust dilution for simple building geometries located in homogeneous terrain environments (e.g., no larger buildings or terrain features nearby) can be estimated using the data and equations presented in the previous sections and in Chapter 44 of the *ASHRAE Handbook—Applications*. However, in critical applications, such as where health and safety are of concern, **physical modeling** or **full-scale field evaluations** may be required to obtain more accurate estimates. Measurements on small-scale models in wind tunnels or water channels can provide information for design prior to construction. These measurements can also be used as an economical method of performance evaluation for existing facilities. Full-scale testing is not generally useful in the initial design phase because of the time and expense required to obtain meaningful information. On the other hand, full-scale testing is useful for verifying data derived from physical modeling and for planning remedial changes to improve existing facilities.

Detailed accounts of physical modeling, field measurements and applications, and engineering problems resulting from atmospheric flow around buildings are available in the proceedings of conferences on wind engineering (see the section on Bibliography).

The wind tunnel is the main tool used to assess and understand the airflow around buildings. Water channels or tanks can also be used. However, the water methods are more difficult to implement and give only qualitative results for some cases. Models of buildings, complexes, and the local surrounding topography are constructed and tested in a simulated turbulent atmospheric boundary layer. The airflow, wind pressures, snow loads, structural response, or pollutant concentrations can then be measured directly by properly scaling the wind, building geometry, and exhaust flow characteristics. Weil et al. (1981), Petersen (1987a), and Dagliesh (1975) found generally good agreement between the results of wind tunnel simulations and corresponding full-scale data. Cochran (1992) and Cochran and Cermak (1992) have found good agreement between the model- and full-scale measurements of low-rise architectural aerodynamics and cladding pressures, respectively.

Similarity Requirements

Physical modeling is most appropriate for applications involving small-scale atmospheric motions, such as recirculation of exhaust downwind of a laboratory, wind loads on structures, wind speeds around building clusters, snow loads on roofs, and airflow over hills or other terrain features. Winds associated with tornadoes, thunderstorms, and large-scale atmospheric motion cannot currently be simulated accurately.

Snyder (1981) gives guidelines for fluid modeling of atmospheric diffusion. This report contains explicit directions and should be used whenever designing wind tunnel studies to assess concentration levels due to air pollutants. ASCE *Standard* 7 and ASCE *Manual of Practice* 67 (ASCE 1999) also provide guidance when wind tunnels are used for evaluating wind effects on structures.

A complete and exact simulation of the airflow over buildings and the resulting concentration or pressure distributions cannot be achieved in a physical model. However, this is not a serious limitation. Cermak (1971, 1975, 1976a,b), Snyder (1981), and Petersen (1987a,b) found that an accurate simulation of the transport and dispersion of laboratory exhaust can be achieved if the following criteria are met in the model and full scale:

1. Match exhaust velocity to wind speed ratios, V_e/U_H.
2. Match exhaust to ambient air density ratios, ρ_e/ρ_a.
3. Match exhaust Froude numbers. $Fr^2 = \rho_a V_e^2/[(\rho_e - \rho_a)gd]$, where d is the effective exhaust stack diameter.
4. Ensure fully turbulent stack gas flow by ensuring stack flow Reynolds number ($Re_s = V_e d/\nu$) is greater than 2000 (where ν is the kinematic viscosity of ambient (outdoor) air), or by placing an obstruction inside the stack to enhance turbulence.
5. Ensure fully turbulent wind flow.
6. Scale all dimensions and roughness by a common factor.
7. Match atmospheric stability by the bulk Richardson number (Cermak 1975). For most applications related to airflow around buildings, neutral stratification is assumed, and no Richardson number matching is required.
8. Match mean velocity and turbulence distributions in the wind.
9. Ensure building wind Reynolds number ($Re_b = U_H R/\nu$) is greater than 11,000 for sharp-edged structures, or greater than 90,000 for round-edged structures.
10. Ensure less than 5% blockage of wind tunnel cross section.

For wind speeds, flow patterns, or pressure distributions around buildings, only Conditions 5 through 10 are necessary. Usually, each wind tunnel study requires a detailed assessment to determine the appropriate parameters to match in the model and full scale.

In wind tunnel simulations of exhaust gas recirculation, the buoyancy of the exhaust gas (Condition 3) is often not modeled. This allows using a high wind tunnel speed or a smaller model to achieve high enough Reynolds numbers (Conditions 4, 5, and 9). Neglecting buoyancy is justified if the density of building exhaust air is within 10% of the ambient (outdoor) air. Also, critical minimum dilution D_{crit} occurs at wind speeds high enough to produce a well-mixed, neutrally stable atmosphere, allowing stability matching (Condition 7) to be neglected (see Chapter 44 of the *ASHRAE Handbook—Applications* for discussion of D_{crit}). Omission of Conditions 3 and 7 simplifies the test procedure considerably, reducing both testing time and cost.

Buoyancy should be properly simulated for high-temperature exhausts such as boilers and diesel generators. Equality of model and prototype Froude numbers (Condition 3) requires tunnel speeds of less than 100 fpm for testing. However, greater tunnel speeds may be needed to meet the minimum building Reynolds number requirement (Condition 4).

Wind Simulation Facilities

Boundary layer wind tunnels are required for conducting most wind studies. The wind tunnel test section should be long enough so that a deep boundary layer that slowly changes with downwind distance can be established upwind of the model building.

Other important wind tunnel characteristics include the width and height of the test section, range of wind speeds, roof adjustability, and temperature control. Larger models can be used in tunnels that are wider and taller, which, in turn, give better measurement resolution. Model blockage effects can be minimized by an adjustable roof height. Temperature control of the tunnel surface and airflow is required when atmospheric conditions other than neutral stability are to be simulated. Boundary layer characteristics appropriate for the site are established by using roughness elements on the tunnel floor that produce mean velocity and turbulence intensity profiles characteristic of the full scale.

Water can also be used for the modeling fluid if an appropriate flow facility is available. Flow facilities may be in the form of a tunnel, tank, or open channel. Water tanks with a free surface ranging in size up to that of a wind tunnel test section have been used by towing a model (upside down) through the nonflowing fluid. Stable stratification can be obtained by adding a salt solution. This technique (towed model in a tank) does not permit development of a boundary layer and therefore yields only approximate, qualitative information on flow around buildings. Water channels can be designed to develop thick turbulent boundary layers similar to those developed in the wind tunnel. One advantage of such a flow system is ease of flow visualization, but this is offset by a greater difficulty in developing the correct turbulence structure and the measurement of flow variables and concentrations.

Designing Model Test Programs

The first step in planning a test program is selection of the model length scale. Choice of this scale depends on cross-sectional dimensions of the test section, dimensions of the buildings to be included in the model, and/or topographic features and thickness of the simulated atmospheric boundary layer. Typical geometric scales range from about 120:1 to 1000:1.

Because a large model size is desirable to meet minimum Reynolds number and Froude number requirements, a wide test section is advantageous. In general, the model at any section should be small compared to the test section area so that blockage is less than 5% (Melbourne 1982).

The test program must include specifications of the meteorological variables to be considered. These include wind direction, wind speed, and thermal stability. Data taken at the nearest meteorological station should be reviewed to obtain a realistic assessment of wind climate for a particular site. Ordinarily, local winds around a building, pressures, and/or concentrations are measured for 16 wind directions (e.g., 22.5° intervals). This is easily accomplished by mounting the building model and its nearby surroundings on a turntable. More than 16 wind directions are required for highly toxic exhausts or for finding peak fluctuating pressures on a building. If only local wind information and pressures are of interest, testing at one wind speed with neutral stability is sufficient.

SYMBOLS

A_L = flow leakage area, Equation (8), ft^2
a = exponent in power law wind speed profile for local building terrain, Equation (4) and Table 1, dimensionless
a_{met} = exponent a for the meteorological station, Equation (4) and Table 1, dimensionless
B_L = larger of the two upwind building face dimensions H and W, Equation (1), ft
B_s = smaller of the two upwind building face dimensions H and W, Equation (1), ft
$C_{p\ in}$ = internal wind-induced pressure coefficient, Equation (5), dimensionless
C_p = local wind pressure coefficient for building surface, Equation (3), dimensionless
$C_{p(in\text{-}out)}$ = difference between outdoor and indoor pressure coefficients, Equation (5), dimensionless
C_s = surface-averaged pressure coefficient, Figure 6, dimensionless
d = effective stack diameter, ft
D_{crit} = critical dilution factor at roof level for uncapped vertical exhaust at critical wind speed (see Chapter 44 of the *ASHRAE Handbook—Applications*), dimensionless
Fr = Froude number, dimensionless
F_{sys} = system flow resistance, Equation (8), dimensionless
g = acceleration of gravity, 32.2 ft/s^2
g_c = gravitational proportionality constant, 32.2 $ft \cdot lb_m/lb_f \cdot s^2$, Equations (2), (6), (7), (10)
H = wall height above ground on upwind building face, Equation (4) and Figure 1, ft
H_c = maximum height above roof level of upwind roof edge flow recirculation zone, Figures 1 and 3, ft
H_{met} = height of anemometer at meteorological station, Equation (4), ft
L = length of building in wind direction, Figures 1 and 2, ft
L_c = length of upwind roof edge recirculation zone, Figure 3, ft
L_r = length of flow recirculation zone behind rooftop obstacle or building, Figures 1 and 3, ft
p_s = wind pressure difference between exterior building surface and local ambient (outdoor) atmospheric pressure at the same elevation in an undisturbed approach wind, Equation (3), lb_f/ft^2
p_v = wind velocity pressure at roof level, Equation (2), lb_f/ft^2
Q = volumetric flow rate, Equation (8), cfm
R = scaling length for roof flow patterns, Equation (1), ft
Re_b = building Reynolds number, dimensionless
Re_s = stack flow Reynolds number, dimensionless
U_{annual} = annual average of hourly wind speeds U_{met}, Table 2, mph
U_H = mean wind speed at height H of upwind wall in undisturbed flow approaching building, Equation (2) and Figures 1, 2 and 3, mph
U_{met} = meteorological station hourly wind speed, measured at height H_{met} above ground in smooth terrain, Equation (4) and Table 2, mph
V_e = exhaust face velocity, ft/s
W = width of upwind building face, Figure 2, ft
δ = fully developed atmospheric boundary layer thickness, Equation (4) and Table 1, ft
δ_{met} = atmospheric boundary layer thickness at meteorological station, Equation (4) and Table 1, ft
Δp_{fan} = pressure rise across fan, Equation (8), psi
$\Delta p_{fan\ eff}$ = effective pressure rise across fan, Equation (9), psi
Δp_{wind} = wind-induced pressure, Equations (9) and (10), psi
ν = kinematic viscosity of ambient (outdoor) air, ft^2/s
ρ_a = ambient (outdoor) air density, Equation (2), lb_m/ft^3
ρ_e = density of exhaust gas mixture, lb_m/ft^3
θ = angle between perpendicular line from upwind building face and wind direction, Figures 4 through 7, degrees

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