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The Estimation of Wind Pressures at Ventilation Inlets and Outlets on Buildings

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ABSTRACT

Two example calculations illustrate the application of information provided in Chapter 14 of the 1989 ASHRAE Fundamentals to the estimation of wind pressures at ventilation inlets and outlets on the exteriors of buildings. Wind pressures are calculated using the local estimated reference mean wind speeds at the building site and pressure coefficients selected from figures provided in Chapter 14 of the Handbook. Calculations include estimation of wind speeds at building sites located significant distances from airport weather data recording stations in a variety of terrains using the "power law" mean wind speed profile equation. Wind frequency data are used to calculate the relative probability of occurrence of wind speed and direction events. Wind tunnel studies are recommended as the best source of wind pressure coefficients for applications where consequences of wind effects could be critical.

INTRODUCTION

The purpose of this paper is to illustrate the application of information on wind pressures on building surfaces provided, or referred to, in the revised Chapter 14 of the 1989 ASHRAE Fundamentals. Due to the length limitations of this paper, only two examples are provided. These examples have been designed to illustrate the estimation of wind pressure at ventilation air inlet and outlet openings on low-rise and moderately tall buildings.

In the case of building projects with limited design budgets, there is little chance of commissioning boundary-layer, wind-tunnel wind pressure distribution studies. Without the benefit of detailed wind tunnel data specific to a particular building project, the data provided in Chapter 14 can be used to estimate the wind effects likely to occur on a building located in level terrain. It is expected that design procedures for tall buildings, in excess of 12 stories, or other buildings on which wind pressure effects could have serious consequences, will include a boundary-layer, wind-tunnel study of wind pressure distributions on external surfaces. Such wind tunnel studies should follow appropriate guidelines, such as those suggested in the ASCE's Manual on Engineering Practice No. 67 (ASCE 1987).

The examples provided in this paper include estimates of the probability of occurrence of wind events based on wind frequency data contained in Degelman 1986). Annual wind frequency data are used to estimate wind pressures at ventilation inlets and outlets in the case of an office building based on the assumption that the building is air-conditioned and that a constant minimal rate of fresh outdoor air is required throughout the year. In the other example, a low-rise industrial building in Atlanta, monthly wind frequency data are used to estimate wind pressure at ventilation fan and ridge vent openings during July, which is the hottest summer month.

Both examples illustrate procedures required to estimate wind conditions at a site remote from the long-term recording site. In most cases the recording site is an airport weather station. These procedures take into account variations in terrain roughness and the need to estimate free stream velocities at a variety of reference heights above ground level.

EXAMPLE NO. 1

This example will illustrate procedures for estimating wind pressures at ventilation inlets and outlets on a moderately sized office building located near the lakefront in Chicago, IL. The lakefront site was chosen to illustrate procedures for accounting for winds approaching a site over this low surface roughness terrain. The use of this moderately tall building, by virtue of its proportions, will also illustrate the application of some pressure distribution data that are not used in the case of low-rise buildings.

Building Characteristics

In this example, the rectangular office building has a height of 100 ft, a length of 100 ft, and a width of 40 ft. The fresh outdoor air inlet opening is 8 ft long and 4 ft high and is located centrally on the upper part of the north-facing wall with its upper edge 6 ft below roof level. The air outlet opening is 8 ft long and 4 ft high and is located centrally at the bottom of the building on the south side with its lower edge located 6 ft above ground level on the south wall (Figure 1).

Local Wind Records

Annual wind frequency data for Chicago, IL, in Table 1 will be used based on the assumption that the building is air-conditioned and that a constant minimal rate of fresh outdoor air is required throughout the year.

While the wind frequency data in Table 1 (Degelman 1986) are convenient and inexpensive, the data lack the precision of more extensive data sets such as Climatology of the United States No. 90. Another, more detailed, source

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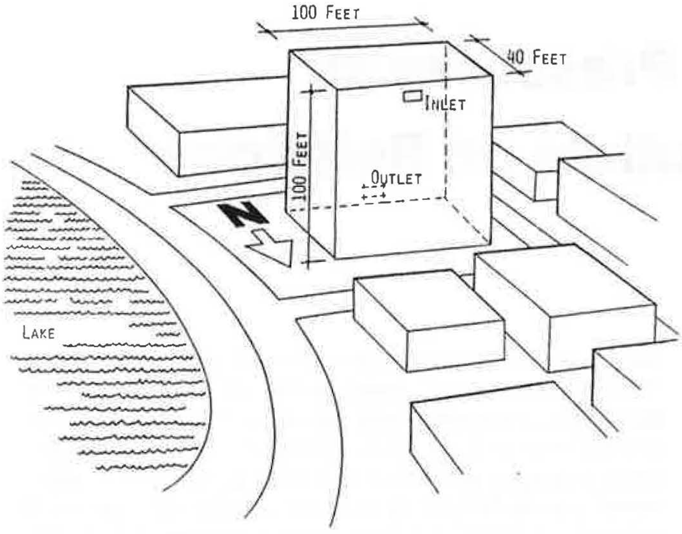

Figure 1 *Sketch of office building in Example 1*

of data is available as custom-assembled data on computer tapes, which give complete data for every wind direction at a recording site for periods of up to 40 years. These more detailed data sets are available from the National Climatic Data Center in Greenville, SC. Data from computer tapes are often fitted to a continuous probability function of a Weibull type to allow estimates of probability to be made for any wind speed. These more detailed data sets should be used when estimating wind effects associated with critical conditions.

Associated Probabilities of Occurrence

An annual percentage probability of occurrence of wind events associated with each of the wind speed interval, wind direction, and time-of-day observations in Table 1 can be calculated by dividing the number of hours observed for any event by the total annual number of observation hours (8760 hours) and multiplying by 100. These percentage probabilities are listed in Table 2.

Site Exposure

The wind speed data in Table 1 can be used only in cases in which a building is surrounded in all prevailing wind directions by a terrain roughness equivalent to that of an airport, which is the terrain roughness in which the wind speed data were recorded. In all other cases, the wind speeds in Table 1 need to be modified to account for the effects of other terrain roughness conditions.

From aerial photographs of the site and its surroundings out to a radius of approximately 3 miles, or alternately from a detailed ground-level visual appraisal, a terrain roughness category from Table 3 is assigned to each prevailing wind direction.

TABLE 1
Annual Summary of Wind Frequencies for Chicago, IL
from Degelman (1986), Cumulative Hours(Prevailing Direction)

Wind Speed Interval (mph	Hours of Occurrence (Prevailing Direction) 1-4am	5-8am	9-12am	13-16pm	17-20pm	21-24pm	Total
0.0- 5.5	303(N)	270(N)	121(N)	54(NE)	164(E)	256(N)	1168(N)
5.5-14.4	957(S)	969(S)	935(*)	930(*)	1024(*)	1003(S)	5818(*)
14.5-21.0	177(NW)	194(NW)	347(SSW)	402(W)	230(W)	170(NW)	1520(W)
21.0	23(NW)	27(WSW)	57(NW)	74(W)	42(W)	31(W)	254(W)

* Denotes no clearly prevailing direction.

TABLE 2
Probabilities of Annual Occurrence (as % of Time)
Calculated from Wind Frequencies for Chicago, IL (Degelman 1986)

Wind Speed Interval (mph)	Percentage Annual Probability of Occurrence (Prev.Dir.) 1-4am	5-8am	9-12am	13-16pm	17-20pm	21-24pm	Total
0.0- 5.5	3.5(N)	3.1(N)	1.4(N)	0.6(NE)	1.9(E)	2.9(N)	13.3(N)
5.5-14.4	10.9(S)	11.1(S)	10.7(*)	10.6(*)	11.7(*)	11.4(S)	66.4(*)
14.5-21.0	2.0(NW)	2.2(NW)	4.0(SSW)	4.6(W)	2.6(W)	1.9(NW)	17.4(W)
> 21.0	0.3(NW)	0.3(WSW)	0.7(NW)	0.8(W)	0.5(W)	0.4(W)	2.9(W)

Note: The symbol * indicates no prevailing direction.

TABLE 3

Terrain Roughness Categories (See Figure 4 in Chapter 14)

Terrain Description	Characteristic Constants a	Zg (ft)	Zo (in)
Ocean or body of water with > 3 mile (5km) expanse.	0.10	700	0.08
Flat terrain with isolated obstacles (airports).	0.15	1000	0.8
Suburban, industrial or forest.	0.28	1300	8.0
Center of large cities.	0.40	1600	79.0

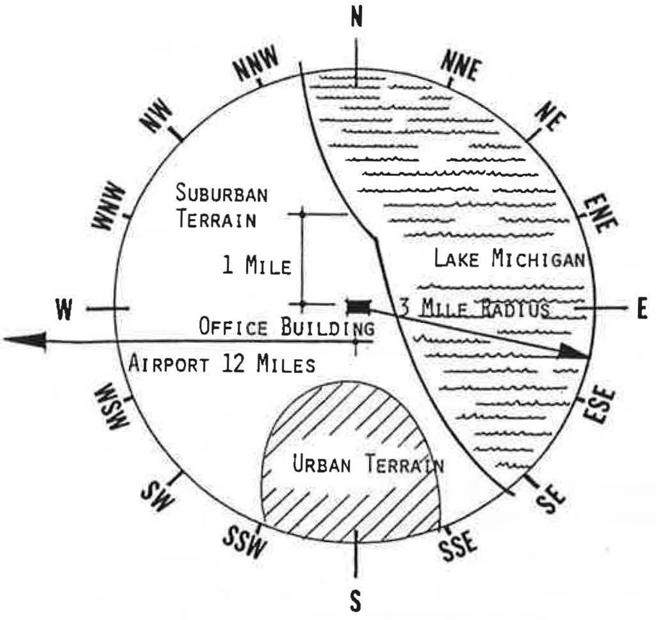

Figure 2 *Location plan for office building in Example 1*

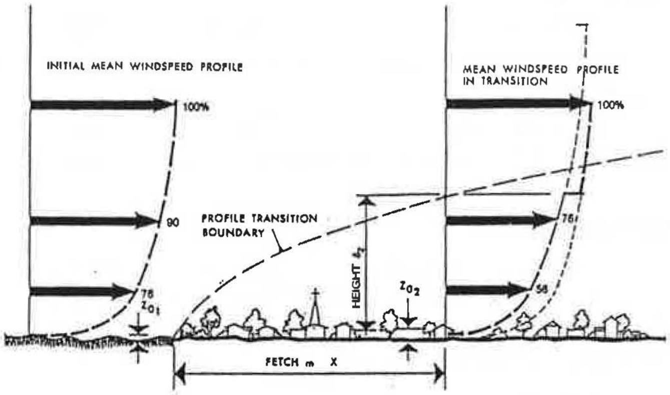

Figure 3 *Development of an internal boundary layer following a change in terrain roughness (Figure 13 in Chapter 14)*

These characteristic terrain roughness constants appear as exponents in Equation 1, which describes the decrease in mean wind speed due to terrain roughness from the undisturbed wind at the gradient height, Z_g, down to a plan-area-weighted average height, Z_o, of obstacles on flat ground. The roughness length, Z_o, is typically 5% to 10% of the average height of obstructions in suburban terrain.

$$V_H = V_{ref}\,(H/H_{ref})^a \qquad (1)$$

where V_H is the mean wind speed at a height $H + Z_o$ above ground level; V_{ref} is the mean wind speed at the mounting height of the recording anemometer, H_{ref}, typically 33 feet; and a is an exponent characteristic of a errain roughness. The anemometer height should be termined along with meteorological data.

Only the terrain roughness effects associated with iling wind directions—north, northeast, east, south, south-southwest, west-southwest, west, and northwest—need to be evaluated. These are the directions of the 16 possible that appear as prevailing wind directions in the wind frequency data for Chicago, IL, in Table 1.

Northern Winds

From the location plan (Figure 2), winds from the north approach over Lake Michigan until they are within approximately 1 mile of the building. Then these winds pass over low, closely spaced (suburban) buildings. When the length (fetch) of new terrain roughness is less than approximately 3 miles, the height of the new developing mean wind speed profile needs to be calculated to determine if the new profile will fully, or only partially, envelope the building, as shown in Figure 3.

From Table 4, it can be seen that by traveling a distance of 1600 ft over suburban terrain from open terrain, the new suburban wind speed profile will develop to a height of 230 ft, more than twice the height of the building in question. Over a longer distance of 1 mile (5280 ft), the suburban wind profile will have developed to an even greater height. This suggests that the building in question will be fully enveloped in a suburban wind speed profile.

TABLE 4
Height of Internal Boundary Layer at a Transition in Roughness
(see Figure 3)

Terrain Transition	Zo_1 (in)	Zo_2 (in)	Travel Distance X Over Zo_2		
			160 (ft)	1600 (ft)	16000 (ft)
			Heights of Internal Boundary Layers		
			(ft)	(ft)	(ft)
Open Country to Suburban	0.8	8.0	36	230	140
Suburban to Open Country	8.0	0.8	30	180	150
Suburban to Urban	8.0	79.0	62	360	2300
Urban to Suburban	79.0	8.0	43	295	1640

Northeastern Winds

From the location plan (Figure 2), winds from the northeast approach over Lake Michigan until they are within approximately 1 mile (5280 ft) of the building and then pass over low, closely spaced buildings.

Eastern Winds

From the location plan (Figure 2), winds approaching from the east approach over Lake Michigan until they are within approximately 60 ft of the building and then pass over the shoreline and a roadway before impacting the building.

Table 4 does not include data on wind speed profile transitions from water surfaces to open country. The closest to this condition would be the transition from open country to suburban. From Table 4, it can be seen that after traveling a distance of only 60 ft over suburban terrain, the new wind speed profile has developed to only 36 ft in depth. Over the much smoother terrain of the foreshore and roadway, the new wind speed profile would probably develop to a height of 2 or 3 ft. This height is not significant relative to the height of the office building in question, so wind speeds at the site can be estimated assuming an open-water wind speed profile for winds from the east.

Southern Winds

From the location plan (Figure 2), winds approaching from the south approach over 3 miles of the city center with many tall buildings and then pass over urban areas for 1 mile (5280 ft) prior to reaching the building site. In this case, terrain roughness has diminished, and the building in question is many times taller than surrounding buildings. The height of the new developing mean wind speed profile needs to be calculated to determine if any of the upper part of the building will be subjected to the old downwind mean wind speed profile.

From Table 4, it can be seen that after traveling a distance of 1600 ft, the new wind speed profile has developed to a height of 295 ft. This is significantly higher (almost three times) than the 100-ft office building in question. This suggests that with a fetch of 5280 ft, it would be appropriate to assume a suburban wind speed profile.

Winds from the South-Southwest, West-Southwest, West, and Northwest

From the location plan (Figure 2), winds from the south-southwest, west-southwest, west, and northwest all approach over suburban terrain for more than three miles.

Determination of Equivalent Reference Wind Speed at Site

In Figure 4, it can be seen that at the gradient heights Z_g (Table 3) for each terrain, the mean wind speed reaches a common value undisturbed by surface roughness. This mean wind speed at the gradient height near the airport recording station can be calculated, using Equation 1, for any mean wind speed measured at a height of 33 ft above ground at the airport.

TABLE 5
Mean Wind Speeds at Gradient Height of 1000 Feet Over Airport Terrain for End Points of Wind Speed Intervals

V_{33} (mph)	V_{1000} (mph)
5.5	9.2
14.4	24.0
14.5	24.2
21.0	35.0

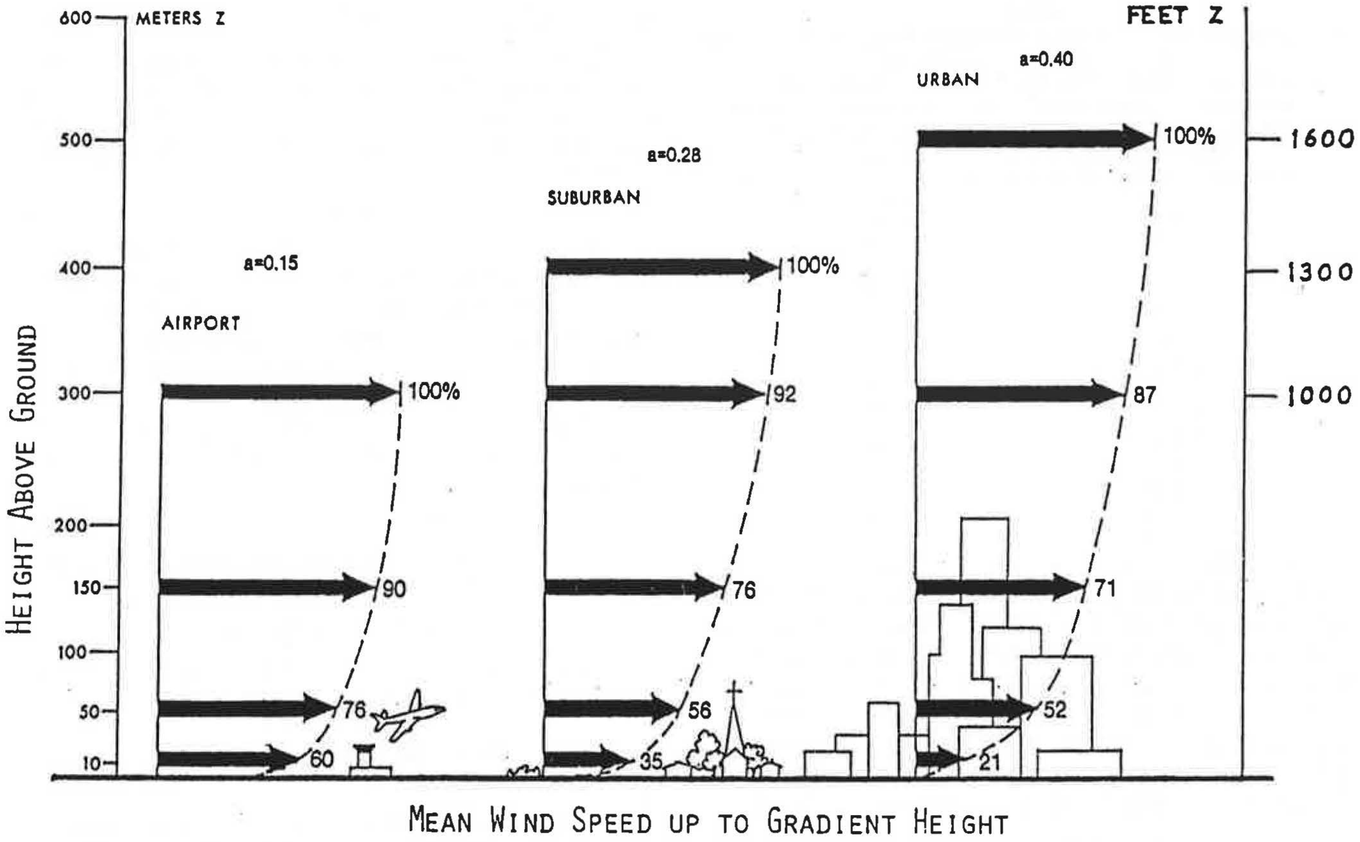

Figure 4 *Typical mean wind speed profiles over different terrain roughness (Figure 4 in Chapter 14)*

For example, the mean wind speed at a gradient height of 1000 ft near the airport anemometer, when the mean wind speed at anemometer height (33 ft) is 5.5 miles per hour (mph) using Equation 1, is:

$$V_{1000} = 5.5(1000/33)^{0.15} = 9.2 \text{ mph}$$

Similarly, mean wind speeds at gradient height Z_g above the airport anemometer for other wind speed interval values are given in Table 5.

The reference heights of wind speeds are referred to from ground level and not the roughness length above ground level. This is common practice in suburban or smoother terrain roughnesses where Z_o, the roughness length, is small compared to building heights and the error incurred is negligible.

For winds approaching from the south-southwest, west-southwest, west, and northwest, the airport wind speeds need to be adjusted for two conditions. First, an adjustment is needed to allow for the transition from the airport mean wind speed profile to the suburban mean wind speed profile. Second, the wind speed associated with the velocity pressure to which pressure coefficient data are referenced needs to be calculated. This reference velocity pressure is usually the approaching mean free-stream velocity pressure of the wind at a height above ground level equal to the height of the building. In this example, an estimate of mean wind speed at 100 ft above ground level is required. These calculations are performed using Equation 1 and the gradient height mean wind speeds in Table 5.

The method for estimating mean wind speeds at particular heights above ground level in this paper is simplified in that boundary layers as shown in Figure 3 may not reach to the gradient height and in such cases different power law exponents apply above the internal boundary layer. Errors incurred by this simplification can be significant where large changes in terrain roughness occur over short fetches.

To estimate the mean free-stream wind speed 100 ft above ground level at the building site from the south-southwest, west-southwest, west, and northwest when there is a 5.5 mph mean wind speed at 33 ft at the airport, we substitute the airport gradient height wind speed for that condition (9.2 mph) into Equation 1 using suburban wind speed profile characteristics of Z_g = 1300 ft and a = 0.28.

$$V_{100} = 9.2\,(100/1300)^{0.28} = 4.5 \text{ mph}$$

Similarly, for other wind speed interval end point values:

$$V_{100} = 24.0\,(100/1300)^{0.28} = 11.7 \text{ mph}$$

$$V_{100} = 24.2\,(100/1300)^{0.28} = 11.8 \text{ mph}$$

$$V_{100} = 35.0\,(100/1300)^{0.28} = 17.1 \text{ mph}$$

Similar calculations are performed for each wind speed profile and each of wind speed intervals and wind speed end point values to produce the values in Table 5.

Calculation of Velocity Pressures for Reference Wind Speeds

Wind pressures on building surfaces, averaged over a period of 10 minutes, can be estimated from the product of the reference velocity pressure and the pressure coeffi-

TABLE 6
Velocity Pressures For Reference Mean Free Stream over Various Terrains for Wind Speeds 100 Feet above Ground Level

Mean Free Stream Wind Speed (mph)	Velocity Pressure (lb/ft^2)
3.0	0.02
4.5	0.05
7.5	0.14
7.6	0.14
7.7	0.15
7.9	0.16
8.0	0.16
11.5	0.33
11.7	0.34
11.8	0.35
17.1	0.73
19.6	0.96
19.8	0.98
19.9	0.99
28.6	2.04
28.8	2.07

cient, C_p, for the point of interest. Pressure coefficients for each wind direction on a particular building shape are determined from wind tunnel studies of building models or publications based on the results of such studies. Reference velocity pressure, p_v, is estimated from the reference mean free-stream wind speed, V_H, at a height, H, equal to the height of the windward wall of the building. The general equation for calculating velocity pressure is:

$$p_v = \rho V_H^2/2 \text{ lb/ft}^2 \qquad (2)$$

(Equation 2 is Equation 7 in Chapter 14 of the Handbook.)

After converting velocity from feet per second to miles per hour and substituting an appropriate value for rho (ρ), the mass density of air (0.0024 slugs/ft^3 at 60°F and standard atmospheric pressure), this equation can be rewritten as:

$$p_v = V_H^2/400 \text{ lb/ft}^2 \qquad (3)$$

When the temperature or atmospheric pressure is significantly different from those used above, the mass density of the air will vary slightly. Appropriate values for mass density of air at other temperatures and pressures can be determined from tables in most basic texts on fluid mechanics.

When using SI units with a mass density of air at 20°C of 1.2 kg/m^3 and wind speed in meters per second, the equivalent equation is:

$$p_v = 0.6\, V_H^2 \text{ Pa} \qquad (4)$$

For a mean free-stream wind speed of 4.5 mph at a wind speed profile height of 100 ft, the velocity pressure is:

$$p_v = 4.5^2/400 = 0.05 \text{ lb/ft}^2$$

Velocity pressure for each of the mean free-stream wind speeds 100 ft above ground level is listed in Table 6.

Selection of Pressure Coefficients from Handbook Data

Pressure coefficients associated with wind pressures at various locations on building surfaces are influenced by

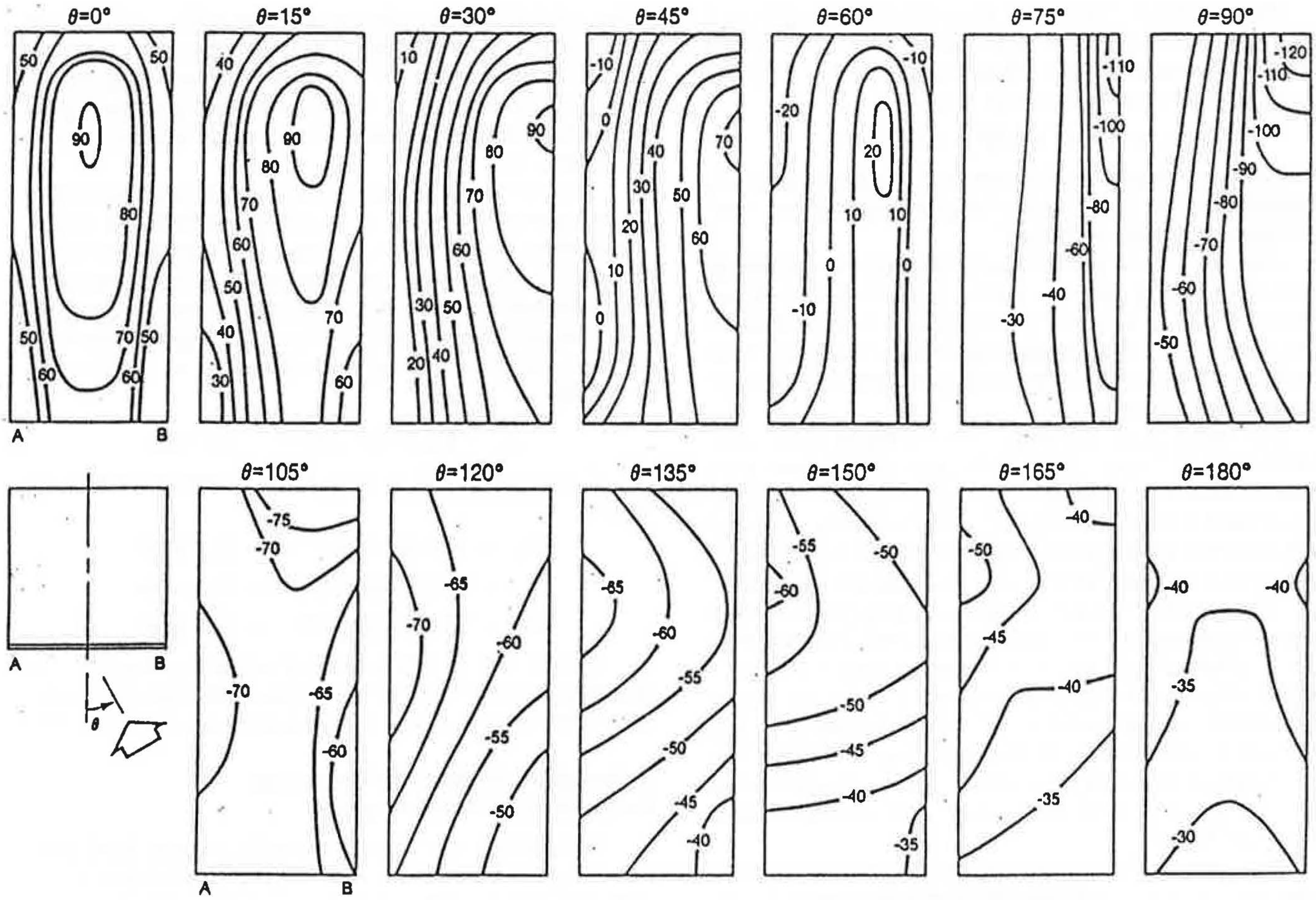

Figure 5 *Mean pressure coefficients (Cp x 100) on a tall building for varying wind directions (Davenport and Hui 1982 [Figure 5 in Chapter 14])*

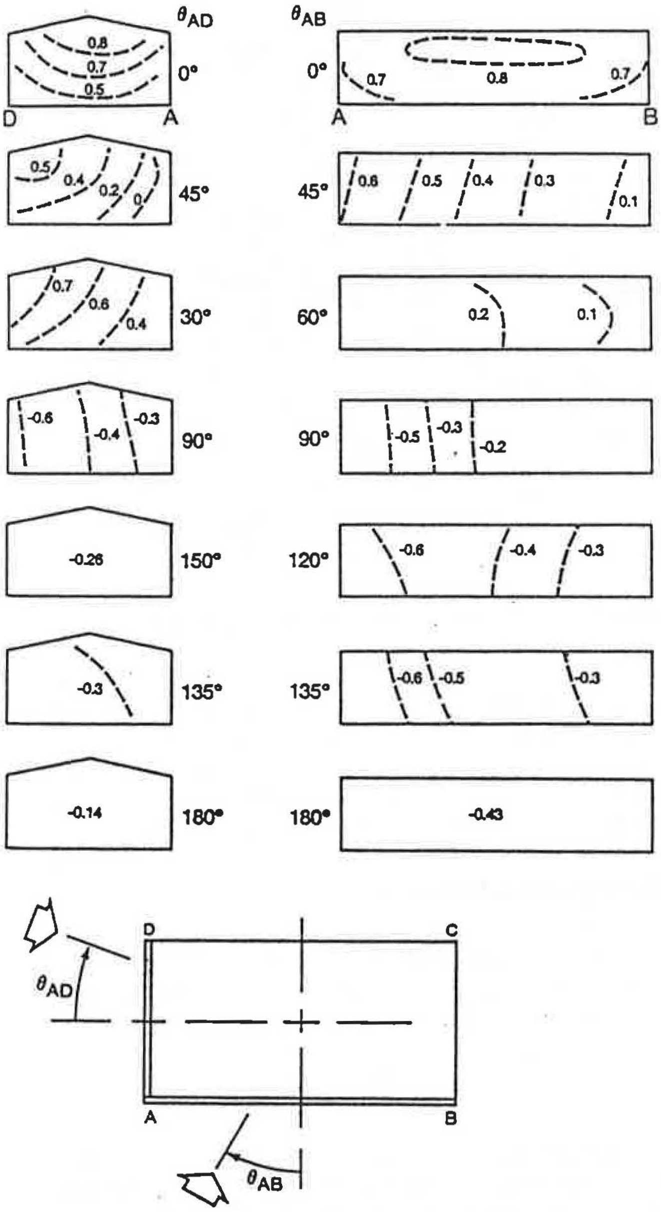

Figure 6 *Mean pressure coefficients on walls of a low-rise building (Holmes 1986 [Figure 6 in Chapter 14])*

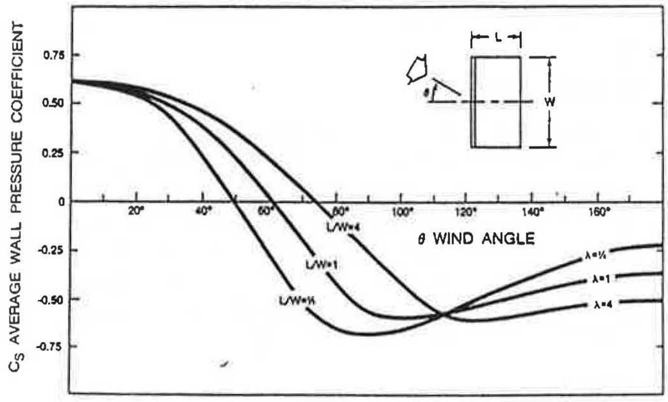

Figure 7 *Variation of wall averaged pressure coefficients for a tall building (Swami and Chandra 1987 [Figure 8 in Chapter 14])*

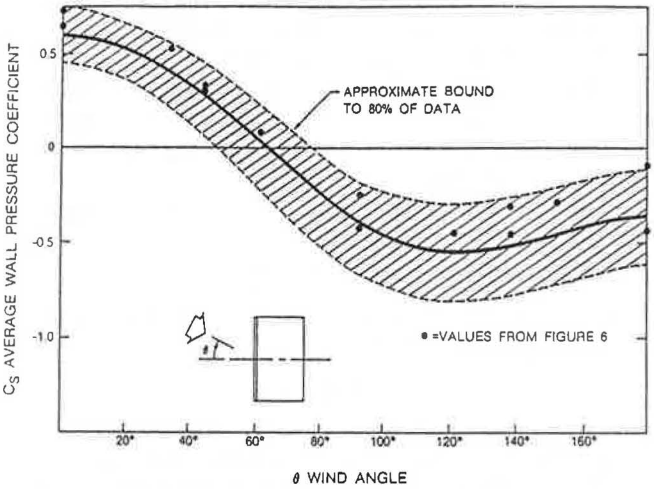

Figure 8 *Variation of wall averaged pressure coefficients for a low-rise building (Swami and Chandra [Figure 7 in Chapter 14])*

the building shape and proportions, wind direction, and nearby obstructions such as other buildings, topographic features, and vegetation. Accurate determination of pressure coefficients can be obtained only from carefully conducted boundary-layer wind-tunnel studies of a model of the building and its surroundings.

Local and surface-averaged pressure coefficient data provided in Chapter 14 of ASHRAE Fundamentals are only meant as a guide, as it is likely that many building configurations will not be specifically accounted for in the graphs. In critical design situations, it is recommended that a wind-tunnel study be performed to determine more accurate pressure coefficient data.

In the case of local pressure coefficients, Chapter 14 of the Handbook divides building forms into high-rise, those with a height greater than three times their cross-wind width in urban terrain (Figure 5), and low-rise, those with a height less than their cross-wind width (Figure 6). Some buildings will fall between these criteria and require interpretive judgment or reference to other sources of pressure coefficients.

Surface-averaged pressure coefficients are provided for high-rise (Figure 7) and low-rise (Figure 8) building forms. High-rise data indicate the influence of length-to-width ratios of the building on surface-averaged pressure coefficients. Width refers to the cross-wind width of the building, length being the along-wind length.

In this example, the proportions of the building (H/W, height-to-width ratios, are less than 3) suggest that low-rise data be used. However, the height of the building is not less than its width, so it does not qualify as a low-rise building either. In such a case, a judgment is needed between the two sets of data.

For wind directions where a 40-ft wall is the windward wall, the height-to-width ratio is:

H/W = 100/40 = 2.5 (close to 3, use high-rise data)

For wind directions where a 100-ft wall is the windward wall, the height-to-width ratio is:

H/W = 100/100 = 1.0

As the office building is tall compared to its surroundings, pressure distributions are likely to be closer to those for a high-rise than for a low-rise building. As a precaution, high-rise surface-averaged pressure coefficients accounting for L/W ratios together with high-rise local pressure coefficients will be considered in deciding on appropriate pressure coefficients.

For wind directions where a 40-ft wall is the windward wall, the length-to-width ratio is:

$$L/W = 100/40 = 2.5$$

For wind directions where a 100-ft wall is the windward wall, the length-to-width ratio is:

$$L/W = 40/100 = 0.4$$

For example, consider the ventilation inlet when winds are from the north. The L/W for this wind direction is 0.4, so the surface-averaged pressure coefficient from Figure 7 at an incidence of 0° is + 0.63. Alternately, from the 0° diagram for local pressure distributions on high-rise buildings in Figure 5, the pressure coefficient in the center top of the surface is between 0.5 and 0.7. As the building in question's north wall is much squarer in proportion than that in Figure 5, a pressure coefficient of 0.6 is probably reasonable.

For the ventilation outlet on the southern face of the building when winds are from the north, the surface-averaged pressure coefficient from Figure 7 is −0.3 at an incidence of 180° with a L/W ratio of 0.4. This is less than the average value of about −0.35 estimated for the wall surface for an incidence of 180° for high-rise local pressure coefficients in Figure 5. Since the data in Figure 5 are a little more detailed, it is reasonable to use −0.3, the pressure coefficient indicated at the center of the bottom of that wall surface.

Pressure coefficients for the inlet and outlet selected for each of the other incident wind directions are indicated in Tables 7 and 8.

Estimation of Wind Pressures at Ventilation Inlets and Outlets

Wind pressures at ventilation inlets and outlets for each prevailing wind direction and for each acting wind speed interval are indicated in Tables 7 and 8. These pressures were calculated by multiplying the appropriate reference velocity pressure by the pressure coefficient associated with the corresponding wind direction. Below these wind pressures are associated annual percentage probabilities of occurrence for each of the wind frequency events. This evaluation cannot account for any wind events that do not include a prevailing wind direction, as pressure coefficients cannot be determined without a wind direction. In this example, these events total 63% of observed wind events. Where such a large proportion of unaccounted wind events is unacceptable, larger, more detailed wind data sets available from the National Climatic Data Center at Greenville, SC, should be used.

EXAMPLE NO. 2

This example will illustrate procedures suggested for estimating wind pressures at ventilation inlets at through-wall fans and ridge outlet vents on a moderately sized warehouse building located in an industrial park situated in undulating forested terrain (see location plan, Figure 9) in Atlanta, GA. This low-rise building was chosen to illustrate the application of monthly wind frequency data and low-rise pressure distribution data, including pressures on roofs.

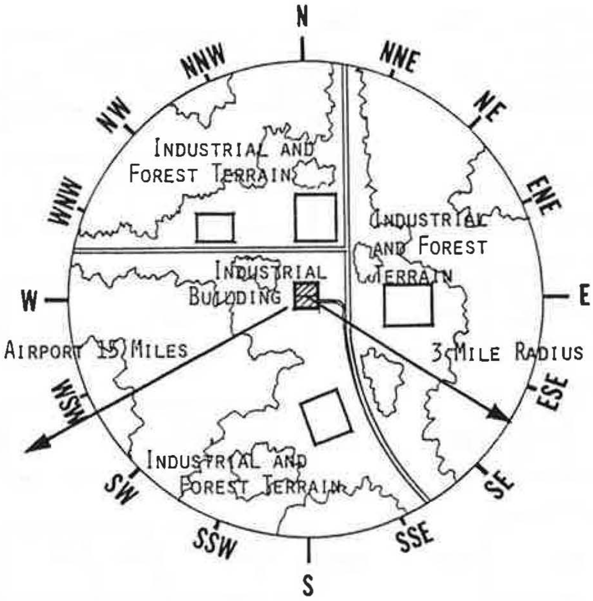

Figure 9 *Location plan for low-rise building in Example 2*

Building Characteristics

In this example, the square warehouse building has a height of 20 ft and a length and width of 200 ft. These dimensions give the following ratio, which will be used to select pressure coefficients for the wall and roof surfaces of the building:

$$L/W = \frac{200}{200} = 1.0$$

For purposes of this example, it is assumed that four through-wall ventilation inlet fans 3 ft in diameter are equally spaced along the top edge of the north-south wall. The ventilation outlet opening is a ridge vent along the central east-west roof ridge that is fitted with flap closures to allow only suction action. The roof pitch is 10°. Wind data for the month of July were chosen because July produces the maximum heat gain conditions in this non-air-conditioned building.

Local Wind Records

In this example, interest is focused on the influence of wind pressures on ventilating fans during the hottest month of the year in a non-air-conditioned building. Monthly wind frequency data in Table 9 come from an ASHRAE publication (Degelman 1986). Hours of occurrence in Table 9 are converted to percentage occurrence for July in Table 10 by dividing the number of hours for each event in the table by the total number of hours observed (744).

Site Exposure

This site's wind exposure is simple compared to that of the site in Example 1. Winds from any compass point will

TABLE 7
Estimation of Wind Pressure at Ventilation Inlets and Outlets for Winds From the N, NE, E, and S in Example 1

Wind Direction	N	NE	E	S
Wind Incidence to Inlet	0 deg.	45 deg.	90 deg.	180 deg.
L/W Ratio	0.4	0.4	2.5	0.4
Wind Profile	Suburban	Suburban	Open Water	Suburban
Free Stream Reference Wind Speed Intervals at 100 feet(mph)	0-4.5	0-4.5	0-7.6	4.5-11.7
Reference Velocity Pressures at 100 feet (psf)	0-0.05	0-0.05	0-0.14	0.05-0.34
Press. Coeff. at Inlet	+0.6 av. +0.6 loc.	+0.2 av. +0.2 loc.	-0.40 av. -0.75 loc.	-0.30 av. -0.38 loc.
Press. Coeff. at outlet	-0.3 av. -0.26 loc	-0.3 av. -0.4 loc	-0.40 av. -0.75 loc	+0.60 av. +0.60 loc
Pressures and Probabilities of Occurrence				
Wind Pressure at Inlet(psf)	positive 0-0.03	positive 0-0.01	negative 0-0.11	negative 0.02-0.13
Wind Pressure at Outlet(psf)	negative 0-0.01	negative 0-0.02	negative 0-0.11	positive 0.03-0.20
Time (hrs)	% Annual Probability During Time Intervals			
1-4 am	3.5%	-	10.9%	-
5-8	3.1%	-	11.1%	-
9-12 noon	1.4%	-	-	4.0%
13-16	-	0.6%	-	-
17-20	-	-	-	-
21-24 pm	2.9%	-	11.4%	-
Totals	10.9%	0.6%	33.4%	4.0%

approach this site over forest and industrial terrain roughness. Wind directions to be considered are the prevailing wind directions indicated in Table 9, which are north, east, southeast, south-southeast, west, west-northwest, and north-northwest.

Determination of Reference Wind Speed

Wind data were recorded at an airport approximately 15 miles away from the site. The reference velocity pressure associated with low-rise building pressure coefficients is from free-stream wind at eave height, in this case 20 ft

TABLE 8

Estimation of Wind Pressure at Ventilation Inlets and Outlets for Winds from the SSW, WSW, W, and NW in Example 1

Wind Direction	SSW	WSW	W		NW	
Wind Incidence to Outlet (deg)	22	67	90		45 to Inlet	
L/W Ratio	0.4	2.5	2.5		0.4	
Wind Profile	Suburban	Suburban	Suburban		Suburban	
Free stream Wind Speed Intervals @ 100 feet (mph)	11.8-17.1	>17.1	11.8-17.1	>17.1	11.8-17.1	>17.1
Reference Velocity Pressure at 100 feet (psf)	0.35-0.73	>0.73	0.35-0.73	>0.73	0.35-0.73	>0.73
Press. Coeff. at Inlet	-0.35 av. -0.40 loc.	-0.60 av. -0.75 loc.	-0.40 av. -0.75 loc.		-0.20 av. -0.20 loc.	
Press. Coeff. at Outlet	+0.55 av. +0.65 loc	0.0 av. +0.05 loc	-0.40 av. -0.75 loc		-0.30 av. -0.26 loc	
Wind Pressures and Probabilities of Occurrence						
Wind Pressure at Inlet (psf)	negative 0.1-0.30	negative >0.55	-0.26-0.55	*>-0.55	-0.07-0.15	*>-0.15
Wind Pressure at Outlet (psf)	positive 0.23-0.47	positive >0.04	-0.26-0.55	*>-0.55	-0.09-0.19	*>-0.19
Time (hrs)	% Annual Probability During Time Intervals					
1-4 am	-	-	-	-	2.0%	0.3%*
5-8	-	0.3%	-	-	2.2%	-
9-12 noon	4.0%	-	-	-	-	0.7%*
13-16	-	-	4.6%	0.8%*	-	-
17-20	-	-	2.6%	0.5%*	-	-
21-24 pm	-	-	-	0.4%*	1.9%	-
Totals	4.0%	0.3%	7.2%	1.7%	6.1%	1.0%

* Probabilities for airport wind speed interval >21 mph.

Note: The 63% remaining wind events have no direction assigned. These events for which no pressures can be estimated occur between 9 am and 20 pm hours and fall within the 5.5 mph to 14.4 mph wind speed interval.

TABLE 9
Wind Frequencies for the Month of July, Atlanta, GA from (Degelman 1986)

Wind Speed	Hours of Occurrence in Time Intervals (Prevailing Dir.)						
Interval (mph)	1-4	5-8	9-12	13-16	17-20	21-24	Total
0.0- 5.5	31(SE)	33(N)	24(N)	13(N)	10(NNW)	27(N)	138(N)
5.5-14.4	92(WNW)	89(WNW)	95(W)	107(WNW)	112(*)	97(E)	592(E)
14.5-21.0	1(E)	2(E)	5(E)	4(E)	2(SSE)	0()	14(E)
> 21.0	0()	0()	0()	0()	0()	0()	0()

* Denotes no clearly prevailing direction.

TABLE 10
Probabilities of Occurrence for July (as %) Calculated from Wind Frequencies for Atlanta, GA (Degelman 1986)

Wind Speed	Percentage Probability of Occurrence in July (Prev.Dir.)						
Interval (mph)	1-4	5-8	9-12	13-16	17-20	21-24	Total
0.0- 5.5	4.2(SE)	4.4(N)	3.2(N)	1.7(N)	1.3(NNW)	3.6(N)	18.5(N)
5.5-14.4	12.4(WNW)	12(WNW)	12.8(W)	14.4(WNW)	15.1(*)	13.0(E)	79.6(E)
14.5-21.0	0.1(E)	0.3(E)	0.7(E)	0.5(E)	0.3(SSE)	0()	1.9(E)
> 21.0	0()	0()	0()	0()	0()	0()	0()

Note: The symbol * indicates no prevailing direction.

above ground level. In a suburban, industrial, or forest terrain, this equates to eave height above ground less Z_o, or 20 ft less 8 in. This is approximately 19 ft in an industrial terrain wind-speed profile.

Following the procedure used in Example 1, the mean wind speeds at the gradient height of 1000 ft near the airport anemometer for each of the wind speeds used to describe mean wind speeds at anemometer height are listed below.

In this example, reference heights of wind speeds are being referred to from ground level and not the roughness length above ground level. This is common practice in suburban or smoother terrain where Z_o is small compared to building heights and the error incurred is negligible.

For winds approaching the warehouse site from any direction, wind speed intervals need to be adjusted for two conditions. The first adjustment is for any change in mean wind speed between the anemometer site and the building site. The second adjustment is for the height at which the reference wind speed above ground at the building site is measured. As pressure coefficients are referenced to velocity pressure at wall height, this is where site wind speeds should be determined.

To estimate the mean free-stream wind speed at wall height, 20 ft above ground level at the building site, when there is a 5.5 mph mean wind speed at 33 ft at the airport, we substitute the airport gradient height wind speed for that condition (9.2 mph) as the gradient wind speed in Equation 1 using industrial speed profile characteristics of Z_g = 1300 ft and a = 0.28.

$$V_{100} = 9.2\,(19/1300)^{0.28} = 2.8 \text{ mph}$$

Similarly for other wind speed interval end point values:

$$V_{100} = 24.0\,(19/1300)^{0.28} = 7.4 \text{ mph}$$

$$V_{100} = 24.2\,(19/1300)^{0.28} = 7.4 \text{ mph}$$

$$V_{100} = 35.0\,(19/1300)^{0.28} = 10.7 \text{ mph}$$

Calculation of Velocity Pressures for Reference Wind Speeds

Calculation of velocity pressures associated with reference wind speeds is performed the same way as in the previous example. Velocity pressures for each of the mean free-stream wind speeds 20 ft above ground level are listed in Table 12.

Selection of Wind Pressure Coefficients

In this example, the building height-to-width ratio of 20/200 is 0.1, which is less than 1, indicating that low-rise pressure coefficient data should be used.

TABLE 11
Mean Wind Speeds at Gradient Height of 1000 Feet
Over Airport Terrain
For End Points of Wind Speed Intervals

V_{33} (mph)	V_{1000} (mph)
5.5	9.2
14.4	24.0
14.5	24.2
21.0	35.0

TABLE 12
Velocity Pressures for Mean Reference Wind Speeds
Over Forest and Industrial Terrain
Reference Height 20 Feet Above Ground Level

Mean Free Stream Wind Speed (mph)	Velocity Pressure (lb/ft^2)
2.8	0.02
7.4	0.14
10.7	0.29

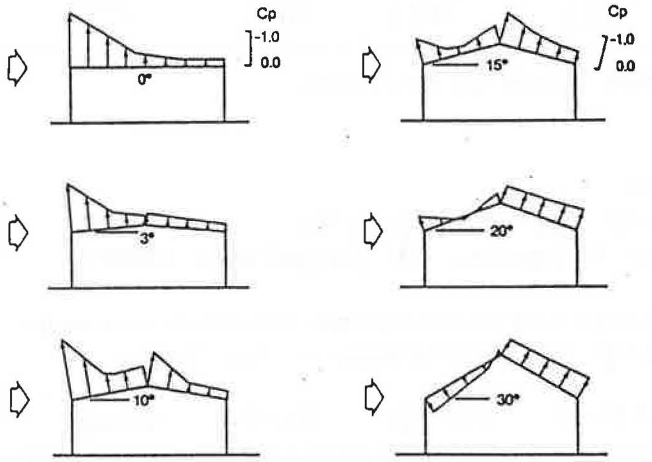

Figure 10 *Pressure coefficients on the roof of a low-rise building (Holmes 1986 [Figure 9 in Chapter 14])*

The building shown in Figure 6 has a greater height-to-length ratio than the 20:200 height-to-length ratio of the building in this example. As a precaution, low-rise surface-averaged pressure coefficients from Figure 8 will be considered together with low-rise local pressure coefficients from Figure 6 in deciding on appropriate pressure coefficients.

For example, consider the ventilation fan inlets when winds are from the north. The surface-averaged pressure coefficient from Figure 8 at an incidence of 0° is +0.6. Alternately, from the 0° diagram for local pressure distributions on low-rise buildings in Figure 6, pressure coefficients along the top edge of the windward wall range between +0.7 and +0.8. As the building in question has much longer walls than that depicted in Figure 6, a pressure coefficient of 0.75 is probably reasonable.

For the ventilation outlet along the roof ridge when winds are from the north, the local roof pressure coefficients from Figure 10 for a roof pitch of 10° are −1.0. These are the only pressure coefficient data provided in ASHRAE Fundamentals for low-rise roofs, so a pressure coefficient of −1.0 is selected.

If this building had been a high-rise, wind pressure coefficients for the roof would have been determined from Figure 11 using appropriate wind incidence and length-to-width ratios.

Pressure coefficients for inlet and outlet can be selected for each of the other incident wind directions and are indicated in Tables 13 and 14.

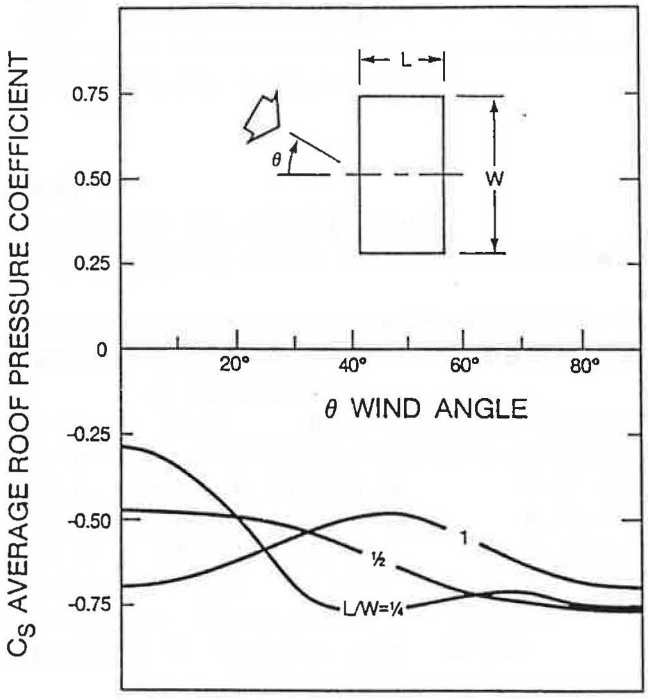

Figure 11 *Wall averaged pressure coefficients for a tall building (Figure 8 in Chapter 14)*

Estimation of Wind Pressures at Ventilation Inlets and Outlets

Reference wind speeds and their associated velocity pressures are provided in Tables 11 and 12. Wind pressures at ventilation inlets and outlets for each prevailing wind direction and for each acting wind speed interval are indicated in Tables 13 and 14. These were calculated by multiplying the appropriate reference velocity pressure by the pressure coefficient associated with the corresponding wind direction.

Below these wind pressures in Tables 13 and 14 are associated percentage probabilities of occurrence during the month of July for each of the wind frequency events. This evaluation cannot account for any wind events that do not include a prevailing wind direction. In this example, these events total 15.1% of observed wind events.

Where a more precise estimate is required, one of the more detailed wind data sets available from the National Climatic Data Center should be used.

TABLE 13
Estimation of Wind Pressure at Ventilation Inlets and Outlets for Winds from the N, E, SE, and SSE in Example 2

Wind Direction	North	East	Southeast	SSE
Wind Incidence to Inlet	0 deg.	90 deg.	135 deg.	157 deg.
Wind Profile	Industrial	Industrial	Industrial	Industrial
Free Stream Wind Speed @ 20 feet (mph)	0-2.8	Int.2.8-7.4 7.4-10.7	0-2.8	7.4-10.7
Reference Velocity Press. at 20 feet (psf)	0-0.02	0.2- 0.14 0.14-0.29	0-0.02	0.14-0.29
Press. Coeff. at Inlet	+0.6 av. +0.75 loc.	-0.3 av. -0.2 loc.	-0.50 av. -0.40 loc.	-0.40 av. -0.40 loc.
Press. Coeff. at outlet	-1.0 loc	-0.5 loc	-1.0 loc	-1.0 loc
Wind Pressures and Probabilities of Occurrence				
Wind Pressure at Inlet (psf)	positive 0-0.015	-0.01-0.07 -0.07-0.15	negative 0-0.008	negative -0.06-0.12
Wind Pressure at Outlet (psf)	negative 0-0.02	-0.01-0.07 -0.07-0.15	negative 0-0.02	negative -0.14-0.29
% Probability During July for Specified Time Intervals				
1-4 am	-	- 0.1%	4.2%	-
5-8 am	4.4%	- 0.3%	-	-
9-12 noon	3.2%	- 0.7%	-	-
13-16 pm	1.7%	- 0.5%	-	-
17-20 pm	-	- -	-	0.3%
21-24 pm	3.6%	13% -	-	-
Totals	12.9%	13% 1.6%	4.2%	0.3%

Application of Wind Pressure Data

The difference in wind pressure between the inlet and outlet should be considered when estimating ventilation fan performance. In cases where the wind pressure at the inlet is greater than the wind pressure at the outlet, fan performance will be enhanced by the wind pressure energy. Alternately, when the wind pressure at the outlet is greater than the wind pressure at the inlet, fan performance will be reduced as the fan works against the extra load created by the wind pressure energy. Where design limits are governed by a minimum allowable air exchange rate, any reduction in fan delivery performance should be carefully

TABLE 14
Estimation of Wind Pressure at Ventilation Inlets and Outlets for Winds from the W, WNW, and NNW in Example 2

Wind Direction	West	WNW	NNW
Wind Incidence to Inlets	90 deg.	68 deg.	22 deg.
Wind Profile	Industrial	Industrial	Industrial
Free stream Wind Speed Intervals at 20 feet (mph)	2.8-7.4	2.8-7.4	0-2.8
Reference Velocity Pressures at 20 feet (psf)	0.02-0.14	0.02-0.14	0-0.02
Press. Coeff. at Inlet	-0.35 av. -0.20 loc.	-0.05 av. +0.15 loc.	+0.50 av. +0.50 loc.
Press. Coeff. at outlet	-0.50 loc.	-1.00 loc.	-1.00 loc

Wind Pressures and Probabilities of Occurrence

Wind Pressure at Inlet (psf)	negative 0.004-0.03	positive 0.003-0.02	positive 0-0.01
Wind Pressure at Outlet (psf)	negative 0.01-0.07	negative 0.02-0.14	negative 0-0.02
% Probability During July for Specified Time Intervals			
1-4 am	-	12.4%	1.3%
5-8 am	-	12.0%	-
9-12 noon	12.8%	-	-
13-16 pm	-	14.4%	-
17-20 pm	-	-	-
21-24 pm	-	-	-
Totals	12.8%	38.8%	1.3%

Note: 15.1% of remaining wind events have no direction assigned. Pressures cannot be estimated for these events which occur between 17 pm and 20 pm hours and fall within the 5.5 mph to 14.4 mph wind speed interval.

checked. Large ventilating fans have been known to stall under adverse wind conditions.

DISCUSSION

Variability associated with wind speed, direction, and frequency poses difficulties in description. Wind frequency data provide an opportunity to describe the probability of occurrence of wind speed and direction events in terms of percentage of time, which is an important consideration with a constantly varying phenomenon such as wind. Probabilities are associated with the wind speed intervals adopted by the data set. Where probabilities of a specific wind speed from a specific direction are required, much more costly statistical analysis of long-term (say, 40 years) wind records is necessary.

The examples provided illustrate that the terrain over which the wind approaches a building can have a significant influence on the wind speed to which the building is exposed. Where terrain changes within 3 miles of a tall building, it is advisable to check the depth of the new mean wind speed profile development to determine if the building will be subjected to a wind speed profile exhibiting characteristics of both terrains.

Most buildings are located significant distances from the nearest airport weather recording station. In such cases adjustments need to be made to airport wind data to account for differences in terrain between the airport and the building site. As wind pressure coefficients are usually referenced to the velocity pressure of the free-stream wind speed at the eave height of a building, it is also necessary to be able to estimate the mean wind speed at various heights above ground in any terrain. These procedures are not complex, but they can be time-consuming and, for that reason, they are better suited to programming for computers.

Pressure coefficient data provided in the Handbook are limited, so they can pose problems for estimating wind pressures on many building types. Users unfamiliar with wind pressure distributions on building forms may have difficulty extrapolating from the distributions shown to buildings of different proportions. These extrapolations sometimes can be difficult even for experts. Reference can be made to other more extensive sources of wind pressure coefficients, but since surrounding buildings and vegetation are also important factors in wind pressure distributions, wind tunnel studies are strongly recommended if accurate results are essential.

CONCLUSIONS

Chapter 14 of the 1989 ASHRAE Fundamentals contains information to assist engineers in estimating a variety of wind effects on buildings. Fundamentals of estimating the effects of airflow around buildings are addressed, and a limited amount of data is provided.

More detailed descriptions of boundary layer aerodynamics can be found in specialized texts on wind engineering (Simiu and Scanlan 1986; Houghten and Carruthers 1976; Aynsley et al. 1977).

Detailed studies will probably require reference to other sources of data, particularly for pressure coefficients. In cases where suitable wind pressure coefficients cannot be found or where buildings of similar or greater height are nearby, an appropriately conducted wind tunnel study of a model of the building and its surroundings is strongly recommended.

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