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CHAPTER 14

AIR FLOW AROUND BUILDINGS

NATURE OF AIR FLOW CONDITIONS: Streamlines and Flow Patterns; Wind Surface Pressures; Dilution of Building Exhaust Gases; METEOROLOGY AND MICRO-METEOROLOGY AFFECTING BUILDING AIR FLOW: Meteorological Air Flow; Downslope Flow; Air Flow Factors Related to Rare Occurrences of Very Strong Winds; WIND EFFECTS ON SYSTEM OPERATION: Pressure Conditions; Building and Building Area Pressure and Flow Control; Inlet and Outlet Design for Weather and Dust Protection; DESIGN TO MINIMIZE REENTRY: Ventilation and Air-Conditioning Inlets and Outlets; Stack Design; Heat Rejection Equipment; Corrosion; PHYSICAL MODELING AND FULL-SCALE MEASUREMENTS: Physical Modeling; Full-Scale Testing

AIR flow around buildings affects (1) worker safety, health, and efficiency; (2) process and building equipment operation and efficiency; (3) equipment and product corrosion; (4) weather and pollution protection at inlets; and (5) ability to control the environmental factors of temperature, humidity, air motion, and contaminants. This chapter contains information for evaluating flow conditions, estimating effluent dilution, and solving problems caused by ambient building air flow and, most importantly, contaminant reentry from exhausts.

Related information may be found in Chapters 11, 13, 22, and 24 of this volume; in Chapters 13 and 15 of the 1978 APPLICATIONS VOLUME; in Chapters 11, 16, 21, and 26 of the 1979 EQUIPMENT VOLUME; and in Chapter 22 of the 1980 SYSTEMS VOLUME.

Air flow around a building is complicated and erratic. Meteorologists can determine probable wind and weather conditions, and micro-meteorology; and industrial hygienists can determine the importance of contaminant exposures and limitations (thus required dilution rates).

Tests by laboratory models or full scale tests of existing buildings may be needed to determine the flow conditions around a building because of its shape and the influence of nearby buildings and topography.

PART I: NATURE OF AIR FLOW CONDITIONS

Wind effects generate surface pressures which vary around a building, changing intake and exhaust system flow rates, infiltration and exfiltration, and the interior pressure. The flow patterns and turbulence of wind passing over the building may cause recirculation of exhaust gases to air intakes.

STREAMLINES AND FLOW PATTERNS

Buildings of even moderately complex shape, such as *L*-shaped structures, formed by two rectangular blocks, may generate flow patterns too complicated to generalize for design. If a building is oriented perpendicular to the wind, it can usually be considered as several independent rectangular blocks, so flow patterns around buildings of simple rectangular cross-section only will be considered. The mean speed of wind approaching a building increases and its turbulence decreases with height above the ground (Fig. 1). Both the upwind velocity profile shape and its turbulence level strongly influence flow patterns and surface pressures.

A stagnation zone exists on the upwind wall (Fig. 1). The flow separates at the sharp edges to generate recirculating flow zones which cover the downwind surfaces of the building (roof, sides, leeward walls) and may extend for some distance into the wake. If the building has sufficient length L in the windward direction, the wind flow will reattach to the building (Fig. 2) and generate two distinct regions of separated recirculating flow: on the building and in its wake.

Surface flow patterns on the upwind wall are influenced mainly by approaching wind characteristics. The higher wind velocity at roof level causes a higher stagnation pressure on the upper part of the wall than near the ground, leading to downwash on the lower half to two-thirds of the building (Figs. 1 and 3a). On the upper quarter to 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 may exist between the upwash and downwash regions, where the surface streamlines pass horizontally around the building (Figs. 1 and 3a). The downwash on the lower surface of the upwind face separates from the building before reaching ground level and moves upwind to form a standing vortex pattern which can generate high velocities close to ground level. *This ground level upwind vortex is carried in a "U" shape around the sides of the building, and is largely responsible for suspension of dust, snow, rain, and leaves which can contaminate air intakes close to ground level.*

Building Flow Zones

In determining the size and shape of flow zones caused by a building, the most important factor is the area, $A = H \cdot W$, facing the wind. Where the height and width of the upwind

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The preparation of this chapter is assigned to the Task Group on Air Flow Around Buildings.

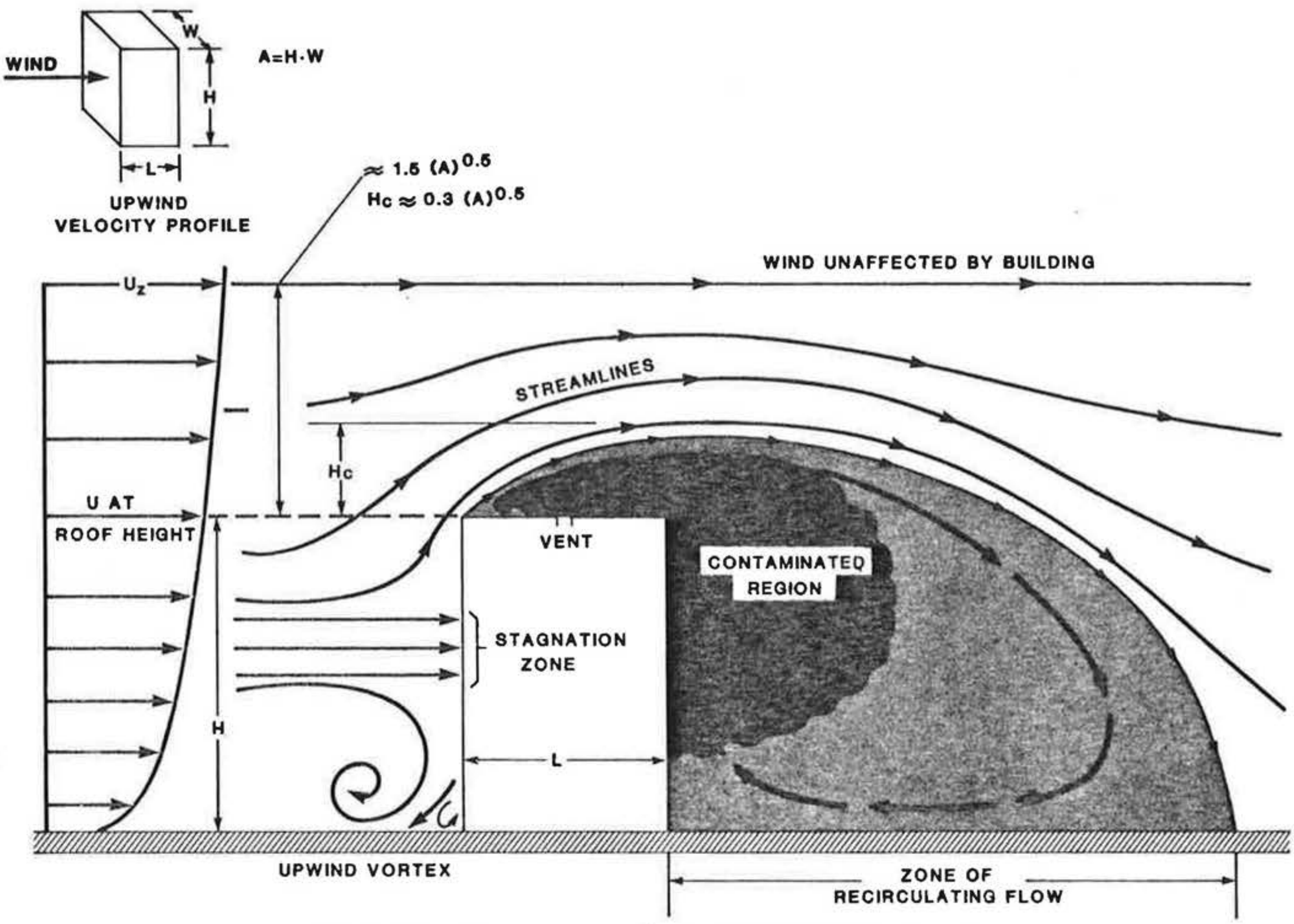


Fig. 1 Centerline Flow Patterns Around Rectangular Building[1,2]

building face are within a factor of eight of each other, the length and height of the recirculation cavity are proportional to the scale factor $(A)^{0.5}$.

On the flat roof and sides of a rectangular building, the separated flow from the upwind edges usually attaches to the building surface if the building length L in the wind direction is larger than about 1.2 $(A)^{0.5}$. Turbulence in the flow separation zone, and in the approaching wind, will cause the reattachment line on the building to fluctuate in a band with time (Fig. 3).

Whether the flow reattaches to the building, or joins the separated wake on the downwind side (Figs. 1 and 2), the maximum height of H_c of the reverse flow region is approximately $0.3(A)^{0.5}$. For a building with a square face ($W = H$) the maximum cavity height over the roof is approximately 0.3 H. Using the length scale $(A)^{0.5}$ it can be seen that cavity height increases with building width. When height H and width W differ by more than a factor of eight, the cavity height H_c *no longer depends on the larger of H or W*. Cavity height and reattachment length may be computed from Table 1.

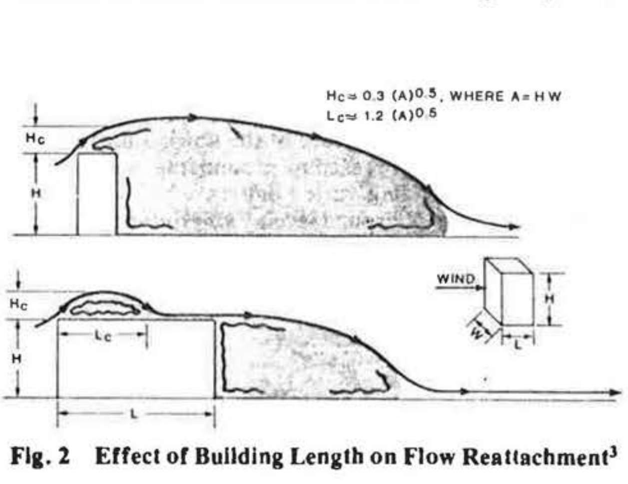


Fig. 2 Effect of Building Length on Flow Reattachment[3]

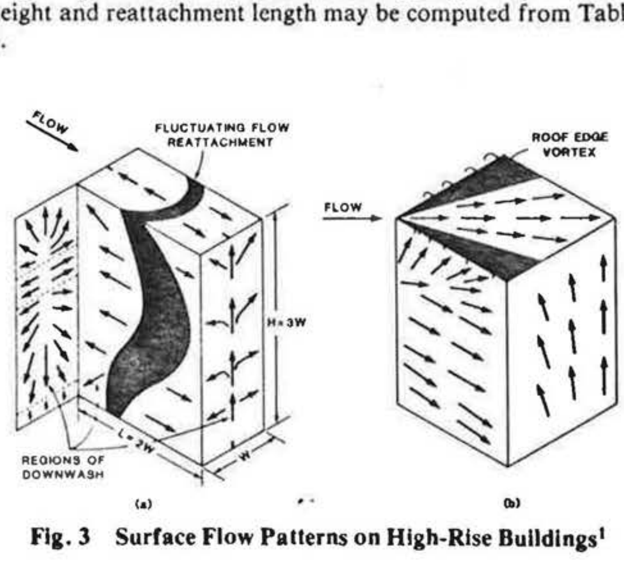


Fig. 3 Surface Flow Patterns on High-Rise Buildings[1]

Table 1 Dimensions of Recirculation Cavity

Ratio of Building Width and Height	Cavity Height, H_c	Cavity Length, L_c*
Less than 8:1	$0.3(HW)^{0.5}$	$1.2(HW)^{0.5}$
Greater than 8:1	0.85 Smaller of H or W	3.4 Smaller of H or W

*Roof recirculation cavity reattachment length (see Fig. 2).

Streamline patterns and cavity shape 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 cavities are not constant over the surface, but will reattach closer to the upwind face of the building along the edges at the roof and ground level (Fig. 3). The height of the recirculation cavity also decreases near roof edges.

The wind above the roof recirculation cavity is affected by the presence of the building, and the flow is accelerated as the streamlines curve upward over the roof, then decelerated as they curve downward into the wake (Fig. 1). The distance above roof level where the building influences the flow is approximately $1.5(A)^{0.5}$.

To avoid entrainment of exhaust gases into the wake, stacks should terminate above the cavity height H_c. Where stacks or exhaust vents discharge within the roof cavity, gases rapidly diffuse to the roof and may enter ventilation intakes or other openings. This effluent will flow into the zone of recirculating flow behind the downwind face and, in some cases, be brought back up onto the roof (Fig. 1).

Zone of Recirculating Flow

The extent of the zone of recirculating flow in the downwind wake of a building depends on the building height H, width W, the roof pitch and, to a lesser extent, the length L in the wind direction. The roof pitch will begin to affect flow when it exceeds about 15°. When roof pitch reaches 20°, the flow will attach to the upwind pitched roof, generating a downwind recirculation cavity larger than for a flat roof of equal wall height (Fig. 4). For roofs with a pitch greater than 20°, the flow over the downwind side of the pitched roof may be assumed to have a reverse flow cavity boundary in the form of a straight line at the same angle as the upwind roof pitch.

The downwind wall of a building faces a region of low average velocity and high fluctuating turbulence. Velocities near this wall are typically less than one-third those at the corresponding upwind wall location. An upward flow exists over most of the downwind wall (Figs. 1 and 3).

If the angle of the approach wind is not perpendicular (less than 90°) to the upwind face, complex flow patterns result. Strong vortices develop from the upwind edges of the roof, causing a strong downwash into the building wake. The high speeds of these vortices cause large suction pressures near roof corners, which can be a hazard to roof-mounted equipment during high winds. When the angle 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. For an approach flow angle of 45°, streamlines remain close to the horizontal in their passage around the sides of the building (Fig. 3b), except near roof level where the flow is sucked upward into the roof edge vortices.

WIND SURFACE PRESSURES

The curvature of wind streamlines passing over a building generates surface pressures dependent on the dynamic pressure of the approach wind.[4,5,6] See Chapter 22.

Approach wind gusts and high levels of turbulent fluctuation generated by flow separation cause surface pressure to fluctuate rapidly with time. If wind direction does not change,

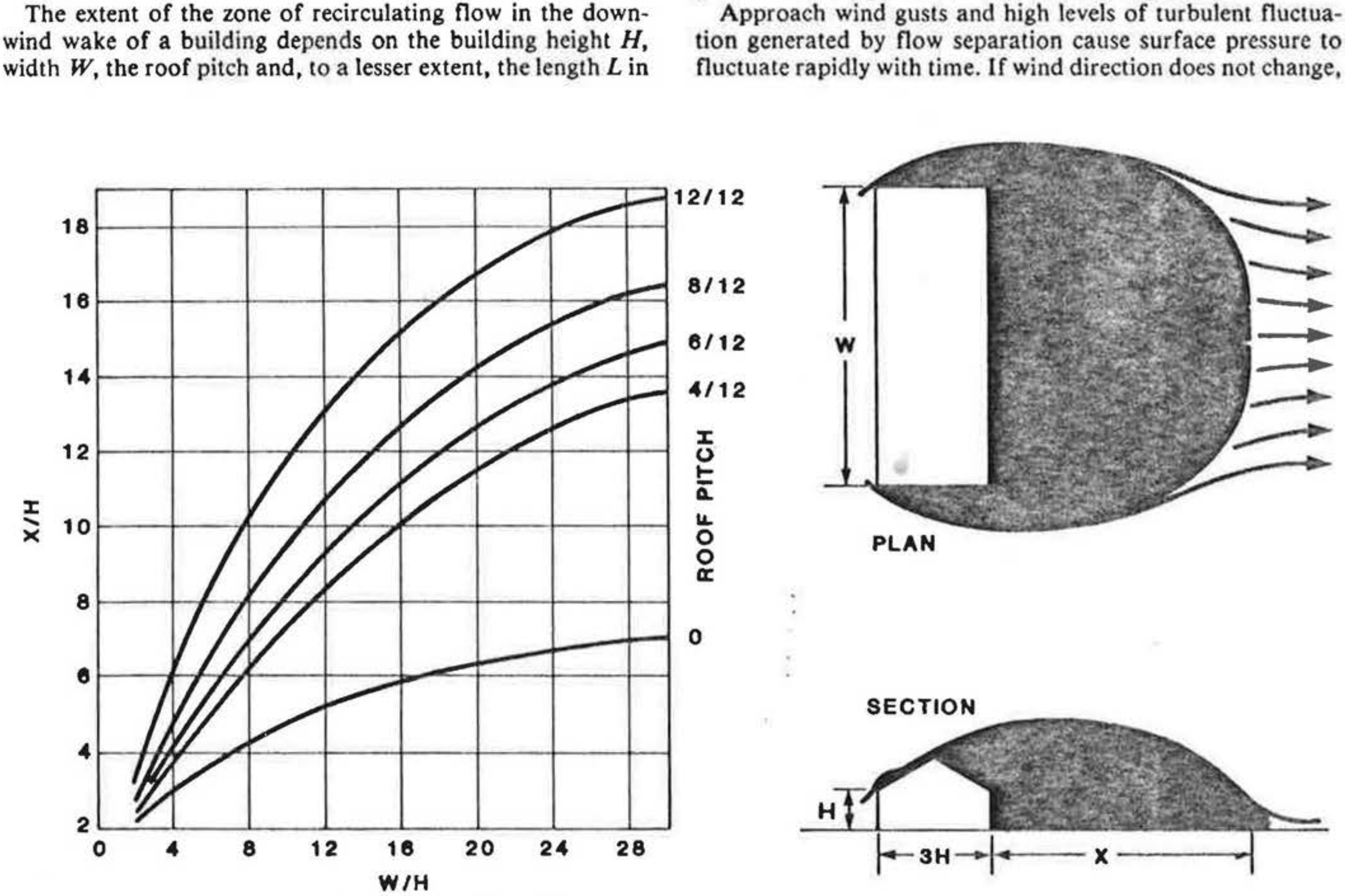


Fig. 4 Effect of Building Width and Roof Pitch on Zone of Recirculating Flow[3]

these fluctuations are random, with time periods as short as 0.5 s. An average surface pressure may be defined over a time period of about 0.6 ks (10 min.). The fluctuating pressures may then be treated as a random variation superimposed on the average pressure.

Both the average and the fluctuating surface pressures are directly proportional to the velocity pressure P_v in the approach wind. Thus,

$$P_v = 0.50\,\varrho U_H^2 \quad (1)$$

$$= 0.6005\,U_H^2 \quad (1a)$$

where

P_v = wind velocity pressure at roof level, Pa.
ϱ = air density, kg/m³.
U_H = wind speed at roof level, m/s.

The constant 0.6005 in Eq 1a is based on a standard air density of 1.201 kg/m³. In English units, designated by the subscript "e,"

$$P_{v,e} = 0.00642\ \varrho_e U_{H,e}^2 \quad (2)$$

$$= 0.000482\,U_{H,e}^2 \quad (2a)$$

where

$P_{v,e}$ = wind velocity pressure at roof level, in. H_2O.
ϱ_e = air density, lb/ft³.
$U_{H,e}$ = wind speed at roof level, mph.

The constant 0.000482 in Eq 2a is based on a standard air density of 0.075 lb/ft³.

Computing the Surface Pressure

The pressure on a building surface, relative to local atmospheric pressure, may be computed from the pressure coefficient C_p defined as

$$P_s = C_p \cdot P_v \text{ or } P_{se} = C_p \cdot P_{ve} \quad (3)$$

where

P_s = wind pressure on building surface, Pa (in. H_2O).
P_{se} = wind pressure on building surface, Pa (in. H_2O).
C_p = pressure coefficient, dimensionless.

The pressure P_s is relative to local atmospheric pressure at ground level away from any influence of the building. For system design, the differential pressure between the building surface and interior must be estimated. Internal pressure depends on building surface pressures, leakage characteristics, and intake and exhaust fan systems (see Chapter 22). Changes in wind direction cause considerable variation in system operating conditions by varying intake and exhaust pressures.

By definition of surface pressure coefficient C_p in Eq 3, positive values are associated with stagnation regions, where surface pressure is higher than the upstream barometric reference pressure. In separated flow regions on the roof, sides, and rear of flat roofed buildings, surface pressures are always less than the upwind barometric reference pressure, and thus have negative coefficients.

Average surface pressure coefficients for a cubical building (Fig. 5) show that C_p varies greatly with position on the

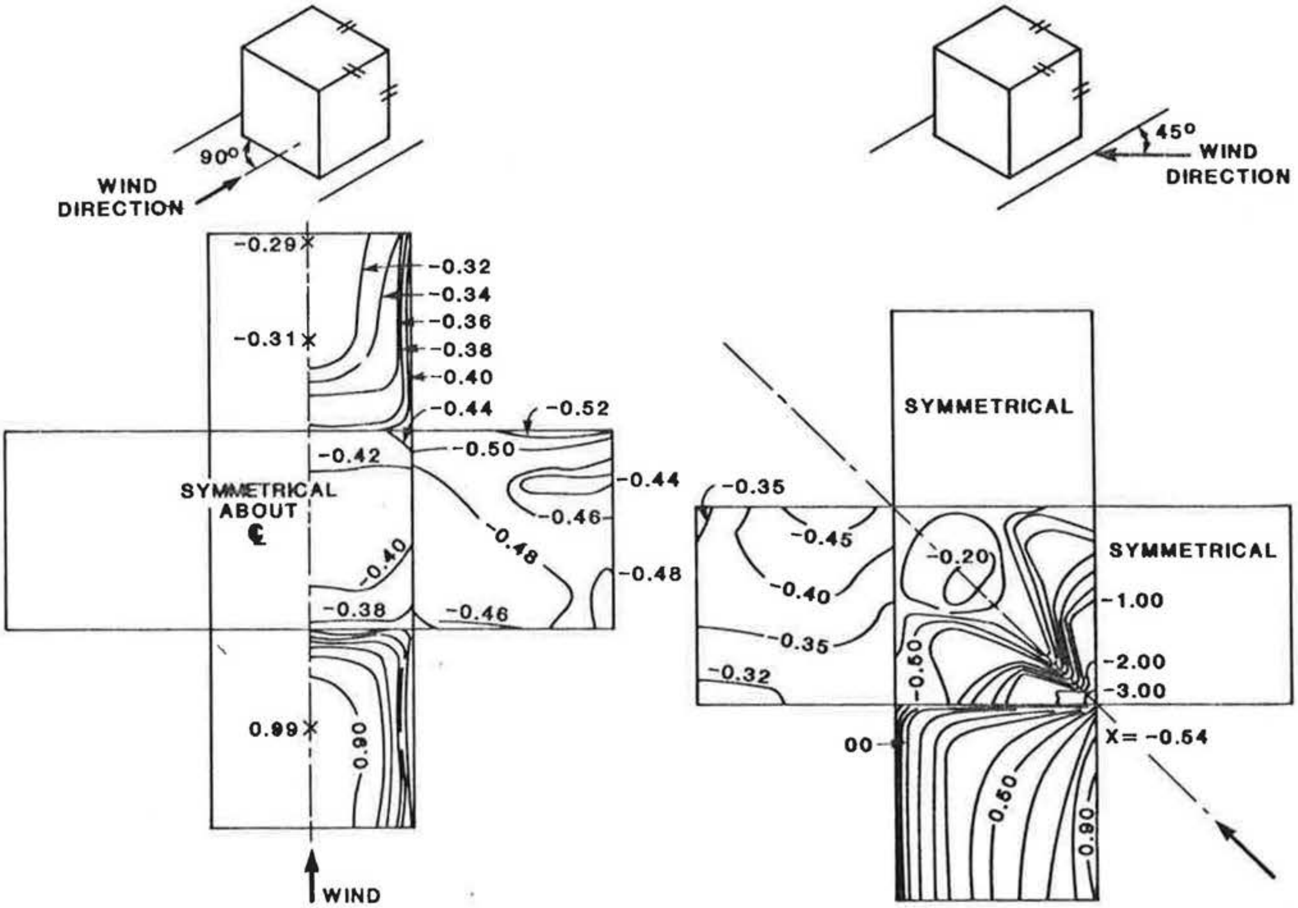
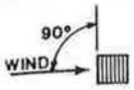


Fig. 5 Surface Pressure Coefficients on Cubical Building[5, 6]

Table 2 Representative Average Surface Pressure Coefficients



Location	Wind Direction 90°	Wind Direction 45°
Upwind walls	+0.8	+0.5
Sides	−0.4	—
Rear	−0.4	−0.5
Flat Roof	−0.5	−0.5

building. When the wind strikes a building at angles other than perpendicular to a wall, the strong vortices along upwind roof edges cause large surface pressure variations on the roof. The high velocities in these roof vortices generate large negative pressure coefficients. The largest variations in pressure occur near edges (Fig. 5), but the center of the roof retains a relatively constant pressure coefficient of −0.4 for the two wind directions considered.

Except for the large variations in pressure close to the edges of building surfaces, the surface pressure coefficients in Table 2 are representative average values applicable to a variety of rectangular building shapes. Surface pressures on pitched roofs depend on roof pitch angle, and whether the pitch is windward or leeward. For a roof pitch less than 20°, negative pressures occur on the windward pitched surface with C_p approximately −1.0 near the upwind edge, and an average value of about −0.3. For pitch in the range 25° to 45° C_p is positive on the windward roof. On the downwind side of a pitched roof the pressure coefficients are relatively constant over the roof surface, with C_p values about −0.5. Wall pressures are relatively unaffected by roof pitch. The differential pressure for an interior space at any point is the difference between external pressure, computed using the coefficients in Table 2, plus the interior pressure (which can be negative).

Surface Pressure on Taller Buildings

On buildings taller than 30 m (100 ft), the lower velocity near ground level affects surface pressure there. This effect may be taken into account by the approximate equation

$$C_{p,z}/C_{p,H} = (H/Z)^{0.5} \quad (4)$$

where

$C_{p,z}$ = average pressure coefficient at height Z, based on velocity U_Z.
$C_{p,H}$ = average pressure coefficient based on velocity U_H at roof height.
Z = height above ground.
H = building height.

Fluctuating Pressure

Wind turbulence and flow fluctuations in recirculating flow zones can generate large momentary pressure fluctuations, which cause vibration and intermittent opening and closing of backflow dampers and other short term variations in system operation. On the upwind surface, turbulence in the approach flow causes pressure fluctuations. Upwind structures and terrain irregularities determine the magnitude of these effects. On downwind walls, the building flow separations also influence pressure fluctuations. Large negative pressure peaks (with C_p from −3.0 to −5.0) occur close to sharp building corners where local vortex systems form. These peaks generally have time periods from one to several seconds.[4]

Effects Caused by Adjacent Buildings

Presence of a new building can considerably alter flow patterns and surface pressures on existing buildings. This may require changes in the height of exhaust stacks, and rebalancing or redesign of intake and exhaust systems. The effects of a nearby building are complicated because, as wind direction changes, the building induces upwind, side, and downwind effects.

An upwind building creates a low velocity, highly turbulent wake which will alter the flow patterns over the downwind building. An upwind building can generate significant effects for a distance approximately twice as long as the zone of recirculating flow which exists behind it. This recirculating flow zone (Fig. 4) depends on the dimensions of the building, and is typically five to ten times the minimum building dimension facing the wind (width W or height H), with a zone of downwind influence 10 to 20 building heights or widths. An adjacent building can cause wind speed to increase due to channeling of flow between the two buildings, resulting in negative pressure coefficients as low as −2.0.

A building downwind of an existing structure generally has little effect on pressure coefficients, but can substantially alter the zone of recirculating flow on the downwind face of the building.

DILUTION OF BUILDING EXHAUST GASES

Dilution theories[7,8] for dispersion of gases from a tall isolated stack cannot readily be applied to diffusion near a building because turbulence around the building greatly affects the rate of dispersion.

A gas mixture discharged from an exhaust within the roof cavity is carried with the flow and is dispersed by turbulence from wind fluctuations and the building wake (Fig. 1). Reverse flow in the recirculation cavity close to the roof often transports significant amounts of exhaust gas opposite to the wind direction, toward the upwind edge of the roof. Although the size of the cavity is substantially independent of wind speed, concentrations within the cavity depend on contaminant emission rate and wind speed. The regions of the cavity in which concentrations exceed the allowable limit may be considered to be contaminated. The size of the contaminated regions will increase with increase of emission rate and decrease of wind speed.

The dimensionless concentration coefficient K is defined as

$$K = CU_H L_d^2/Q \quad (5)$$

where

C = volume fraction (concentration) of stack gas contaminant at roof level.
U_H = wind speed at roof height approaching the building, m/s (fpm).
L_d = gas diffusion length scale related to building size, m (ft).
Q = volume flow rate of *contaminant* in stack gas, L/s (cfm).

NOTE: Close to the building, turbulence generated by the building dominates background atmospheric turbulence. Under these conditions it is logical to define $L_d = (A)^{0.5}$ where A is the area of a building wall facing the wind (see Refs 2, 9, 10, and 11). The value of L_d should be as specified in each experimental study.

The stack exhaust contaminant concentration C_e and concentration coefficient K_e are given by

$$C_e = Q/Q_e = Q/A_e V_e \quad (6)$$

$$K_e = C_e U_H L_d^2/Q = L_d^2 U_H/A_e V_e = AU_H/A_e V_e \quad (7)$$

where

A_e = internal stack area, m² (ft²).
Q_e = total exhaust gas flow rate, L/s (cfm).
V_e = gas velocity in stack, m/s (fpm).

The dilution is defined as

$$D = C_e/C = K_e/K \quad (8)$$

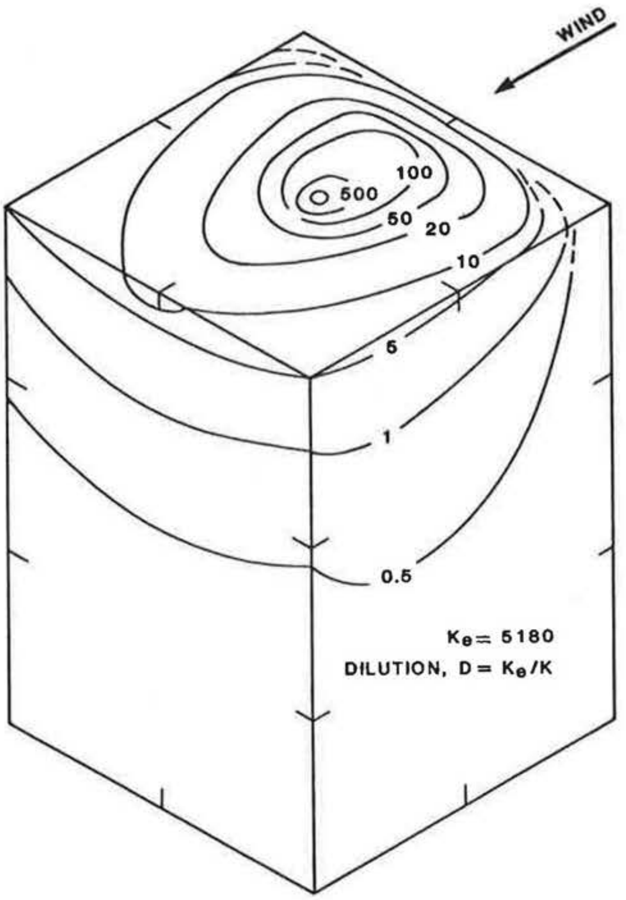


Fig. 6 Typical Isopleths for Centrally Located Roof Vent[1,2,9]

$D = 1$ at the stack, where $C = C_e$ and approaches ∞ as C approaches zero at large distances from the stack. At any specific distance from the stack, the minimum dilution factor D_{min} occurs at a point in the exhaust plume, usually the centerline, where C_{max} is observed:

$$D_{min} = C_e/C_{max} = K_e/K_{max} \tag{9}$$

Estimating Contamination from Exhaust Units

The most accurate method of estimating intake contamination from exhaust vents is to use experimentally determined K isopleths[2, 9, 10, 11] (Fig. 6) to obtain an expected value of K at an intake, and then convert K to a real concentration C by Eq 5. Past studies have covered only a small number of the more elementary building shapes. Model testing is necessary to study the diffusion conditions for proposed complicated structures. For existing buildings a number of methods of field testing are available.

K isopleths for block buildings with uncapped vents in a uniform wind stream have been determined by Ref 10 and further specialized studies,[4, 12, 13] and in an atmospheric boundary layer by Refs 2 and 9. The last studies, with very low vent discharge velocities, simulated the worst conditions (such as for capped vents or louvered openings) to estimate minimum dilution conditions.

The boundary layer in the approach flow modifies the shape and size of the reversed flow regions around the building, altering the surface concentrations. For tall buildings whose roofs are above the most intense atmospheric turbulence and wind shear, these effects are relatively small, and the most important factor in avoiding recirculation (reentry) is stack height. Vent caps or horizontal louvered discharges prevent the vent jet penetrating the top of the roof cavity into the free airstream because of its exhaust momentum and/or buoyancy. *In exceptional cases, where it may be necessary to rely on jet penetration to dilute the contaminant in lieu of a stack discharging above the cavity, expert advice should be sought regarding emission velocity and the effectiveness of physical stack height.*

Substantial separation between exhaust and inlet may be adequate to keep the inlet concentration below an allowable concentration, C_{allow}. This requires that the dilution be greater than

$$D_{allow} = C_e/C_{allow} \tag{10}$$

Estimating Minimum Dilution: Special Cases

Approximate equations have been developed to estimate minimum dilution around building surfaces. They should be used with caution and within the limits of supporting research. For simple block buildings, the equations provide means to determine relative dilution for various surface locations and heights of exhausts and intakes. This helps to establish acceptable locations of the exhausts and intakes.

As wind speed decreases, dilution decreases. At low wind speeds and appreciable stack velocity and/or temperature, the vertical momentum and buoyancy of the exhaust jet will cause high dilution rates not accounted for by the equations. Stack height is also important. Consequently, as wind speed decreases, dilution will decrease until, at some critical low speed, it will begin to *increase* with further *decrease* in wind speed, as jet momentum and buoyancy become dominant factors. These wind velocities may also be the velocities at which maximum neighborhood pollution occurs.

Eq 11 was developed from studies with flush or short vents on block buildings.[1,2,9,14] Low stack velocities simulated minimum dilution conditions where stack caps or louvered vents might be used (this in no way endorses their use):

$$D_{min} = 0.11\,(U_H/V_e)\,[r/\sqrt{A_e}\;]^2 = 0.11\,U_H\,r^2/Q_e \tag{11}$$

$$\begin{array}{l}\text{Minimum dilution,}\\ \quad\text{vent to intake}\end{array} = \frac{0.11\left[\begin{array}{l}\text{Design wind}\\ \quad\text{speed, m/s (fpm)}\end{array}\right]\left[\begin{array}{l}\text{Distance from exhaust stack}\\ \quad\text{to contaminated intake, m (ft)}\end{array}\right]^2}{\left[\begin{array}{l}\text{Total stack gas}\\ \quad\text{flow, L/s (cfm)}\end{array}\right]}$$

NOTE: In computing the distance r from the exhaust to the intake, the stack height above roof level should be added to the shortest distance from the stack base to the intake.

Eq 12 is for estimating minimum dilution between uncapped flush vents and intakes in the building surfaces and roof penthouses on simple and complex block buildings. It is a special case which provides a lower bound (minimum dilution estimate) based on observed data:[10]

$$D_{min} = [1 + 0.132\,S/\sqrt{A_e}\;]^2 \tag{12}$$

where

S = *stretched string* separation distance, exhaust to intake, m (ft).
A_e = internal exhaust stack area, m^2 (ft^2).

NOTE: while wind speed and stack discharge velocity are not elements of Eq 11, it was developed from data at velocities which indicated the worst conditions, i.e., *minimum dilution*. The stack to wind velocity ratios, V_e/U_H, were in the range of 0.5 to 2.2.

The required minimum separation distance from exhaust vent to inlet may be estimated by applying Eq 10, and Eq 11 or 12, and solving for S or r. Eq 11 is not applicable for very short distances from the exhaust, and should be used only when a predicted minimum dilution $D_{min} > 10$ is obtained. When $D_{min} < 10$, the intake is close enough to the exhaust vent to be influenced by local wind patterns and the jet of the exhaust gas.

At short distances, Eq 12 predicts lower values of D_{min} than does Eq 12. At large distances the two equations approach one another. Eqs 11 and 12 were developed from simple plume models in local diffusion regions unaffected by building size. In using Eq 11, the dilution should be estimated by assuming that $U_H = U_{crit}$, at which minimum dilution takes place. Wind speed increases with height and may be estimated from:

$$U_H/U_{ref} = [Z/Z_{ref}]^{0.25} \qquad (13)$$

where U_{ref} is a meteorological reading and Z_{ref} is the height at which the reading was taken, usually about 10 m (30 ft). The correction need be made only for tall buildings. In the absence of detailed information on the exhaust jet plume rise, U_{crit} may be assumed to occur when U_{ref} is about 2.0 m/s (4.5 mph).

The dilution factors predicted by Eqs 11 and 12 represent minimum values over averaging periods of 0.6 to 1.8 ks (10 to 30 min). To predict peak concentrations that may occur for shorter periods, average concentrations should be multiplied by factors of 2 to 5.[1]

Because of the highly nonlinear nature of dilution, the designer must be very cautious in compromising the optimum stack height with any architectural constraint. If stack height is reduced 50%, roof level concentrations near the stack can increase by a factor of 10 or more.

PART II: METEOROLOGY AND MICRO-METEOROLOGY AFFECTING BUILDING AIR FLOW

METEOROLOGICAL AIR FLOW

Air flow around buildings is subject to many meteorological variables within the atmosphere. The meteorological air flow is (1) that flow which prevails upwind from the building beyond any flow distortion the building causes; (2) that flow which prevails above the vertical disturbance the building causes; and (3) that flow downwind from the building beyond the end of any disturbance the building causes.

Recorded wind measurements are based primarily on observations near airport runways of metropolitan areas. The exposure of a wind unit at about 10 m (33 ft) above ground at one airport cannot be representative of air flow throughout the metropolitan area, particularly along a river, sea coast, lake edge, or near irregular terrain with a height differential of 100 m per km (slope of 1:10). Most cities are in such locations. This indicates a need for small weather stations near industrial buildings, complex arrays of buildings, and/or laboratories which have contaminant problems. The daily cycle of temperature fluctuation [2 to 15°C (3.6 to 27 F)] produced by daytime presence and nighttime absence of solar radiation permits having coldest air near the ground at night and hottest air near the ground in the day.

DOWNSLOPE FLOW

As the sun disappears in the evening, radiation from the earth's surface toward outer space produces a layer of colder air near the ground. Along sloping terrain the cooler air develops a net downslope motion. Along broad river valleys a

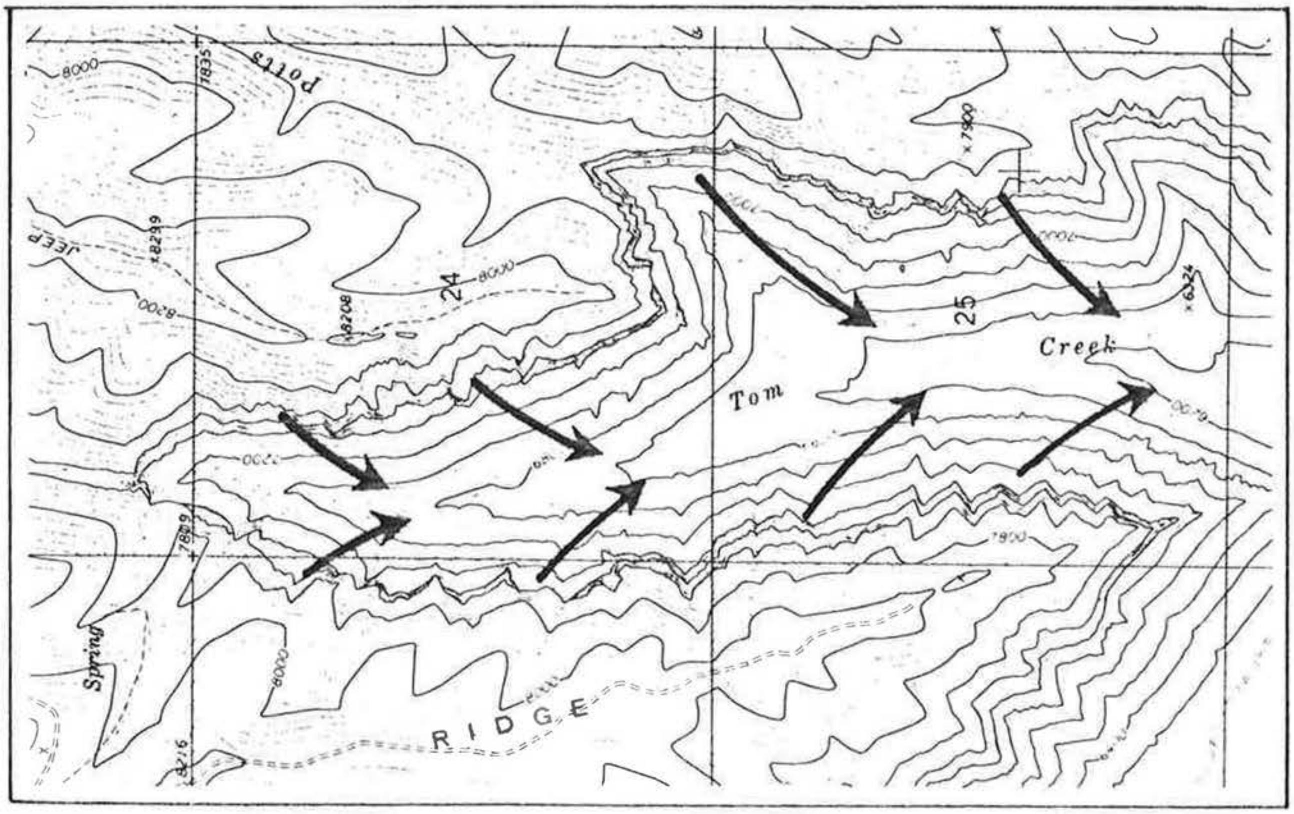


Fig. 7 Typical Pattern of Nighttime Downslope Air Flow

herringbone pattern of downslope flow from both shoulders drains toward the center of the valley (see Fig. 7). As darkness continues the air temperature near the ground continues to drop. There is a net flow toward the valley center and a gradual deepening of an air layer cooler than the air above. This produces a stable air condition—warmer air above colder air.

Winds measured on the shoulder of a river valley show a downslope drainage flow direction which may be 90° different from the flow at a similar point on the opposite shoulder of the valley during nighttime and early forenoon.

Effluents from elevated stacks having both high temperatures and high exit velocities will rise to a level of equivalent buoyancy generally well above the "cavity" influences of the building from which the effluent is released, then follow a nearly horizontal pattern. The layer of cool stable air is initially thin and very near the ground surface in early evening. Some time lag occurs before this layer of colder air is sufficiently deep to envelop the total elevated effluent plume.

A net inward flow moves toward the center of metropolitan areas for air heated by manmade heat sources over which it passes, producing a warm area—a "heat island" (see Fig. 8). The size of the heat island varies with city size, terrain features, and typical speed of downslope drainage air flow. Heat islands are most pronounced in winter. The air near the center of the heat island, 3 to 7°C (5.4 to 12.6 F) warmer than suburban surrounding air, tends to rise and move toward lower ground at a level above colder air which collects in the valley downstream of the metropolitan area. The vertical dimension of the heat island is generally between 200 and 500 m (650 to 1650 ft) with air flow conditions distorted by the irregular patterns of buildings of the metropolitan core area, and winds are light and variable near the center. In nonurban areas, the herringbone drainage flow toward the center of broad valleys remains the dominant air flow pattern at night.

In irregular terrain it is typical to have a near reversal of air flow during forenoon hours (see Fig. 9). Solar heating of the ground in the morning forces the end of downslope drainage flow in irregular terrain. The layer of cooler air near the ground is eliminated first on east-facing slopes. On the shoulders of the valley the cooler air layer is not as deep as that over the valley center. As the air near the surface gains heat from the sun, small segments of warmer air rise and are replaced with nearly equal small segments of cooler air from directly above. Rapid vertical mixing generally begins first above the ridges in the terrain and as surface heating increases, more newly warmed air rises than can be replaced by the slightly cooler air directly above. Some replacement air moves horizontally from near the center of the valley in a general upslope motion toward the higher ground on both sides of the valley during late morning. Unstable air conditions prevail during the warm midday. The daily cycle of temperature difference is thus matched by a corresponding daily cycle of air flow patterns near the ground. In many metropolitan areas this air flow exchange can be nearly a direct reversal, almost always with low wind speeds of less than 5 m/s (11 mph).

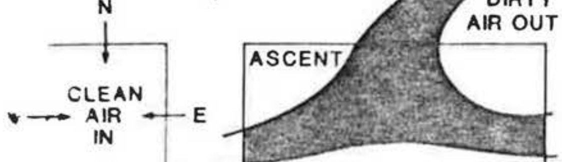


Fig. 8 Heat Island Mechanics. Net In-Flow, Thermal Rise, and Out-Flow of Polluted Air over Major Metropolitan Area

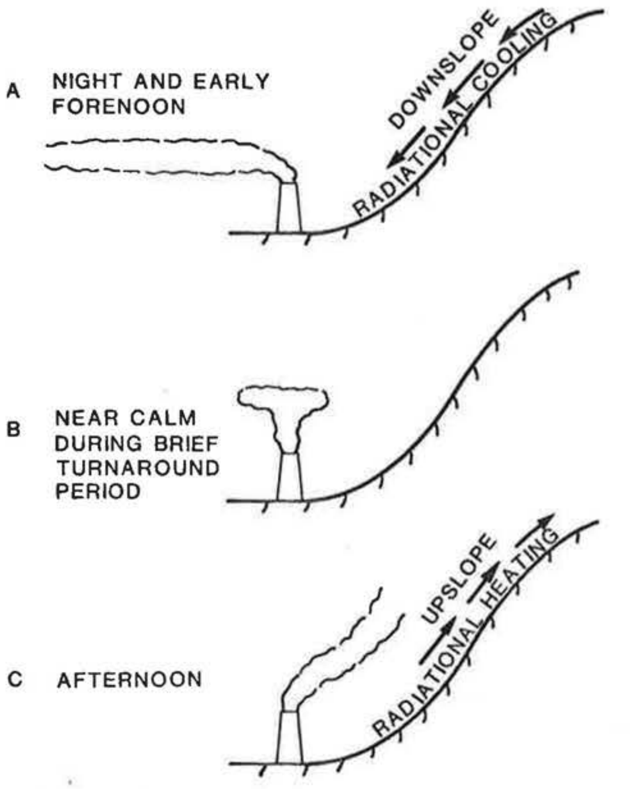


Fig. 9 Downslope and Upslope Exchange of Air Motion near Mountain Slopes Which Can Affect Behavior of Effluents from Stacks Located in Nearby Valleys

When major storms pass an area, stronger wind speeds develop with the possibility of some precipitation. Centers of low and high pressure are identifiable on weather maps. The air flow is then dominated by the pressure pattern, modified only slightly by local terrain features. Frequency arrays of all wind directions and speeds measured at a given location are the composites of many subsets of weather conditions, which may produce different and important air flow patterns around a particular building at a particular site.

At many locations the direction of air flow associated with extended periods of active precipitation is limited to a particular direction, semicircle, or quadrant. The air flow associated with downslope drainage and stable air conditions may carry away effluents from a particular building in a very limited range of direction. Air flow from some other building upwind from the building being considered may have a strong influence on stable air flow patterns. Influences of surrounding buildings are least during periods of unstable air conditions when surface heating forces rapid vertical mixing.

Use of prevailing wind direction for all problems can lead to serious errors. For instance, the prevailing wind at Chicago is from the northwest, but the direction coincident with high air pollution episodes is predominantly from the southeast. From any set of historical wind records one particular direction will have a somewhat higher frequency than all others.

This most frequent direction is, however, often considered the prevailing wind. The frequency of winds from some other direction, often more than 45° away, may be almost equally high. Wind speed ranges may also be important to the particular problem at hand.

When horizontal flow is strong, as in storm periods when cloud cover disrupts the typical radiation exchange, the temperature decrease with height above ground is very near the adiabatic lapse rate (which directly reflects the decrease in temperature due only to the decrease in air density).

There is a typical wind speed profile with increasing height. For buildings taller than 100 m (330 ft), the difference between the meteorological air flow near the ground and the top of the building typically is 2 to 3 m/s (4.5 to 6.7 mph), and may be as great as 10 or 15 m/s (22.4 or 33.5 mph). For buildings several stories in height, no single wind speed is representative of the meteorological air flow approaching the structure. Multiple classes of wind speeds to fit several segments of the building height increase the complexity of calculations of air flow around the building. The calculations are needed, however, for a good approximation of the pattern of the disruptive effects of the building itself.

Stronger winds generally have some superimposed gustiness (rapid changes in wind speed with almost no change in direction). Gust factors tend to decrease with increasing wind speed. A gust factor of 1.4 for a wind of 15 m/s (33.5 mph) would produce some peak gust readings of 21 m/s (47.0 mph). Gust factors between 1.2 and 1.3 are much closer to measured records for very strong winds. At light wind speeds, 5 m/s (11.2 mph) or less, intermittent gusts can have speeds which are double the steady wind speed.

AIR FLOW FACTORS RELATED TO RARE OCCURRENCES OF VERY STRONG WINDS

The rare occurrences of severely strong winds will have important effects on air flow around buildings, primarily involving structural considerations: (1) general air flow patterns, (2) roof considerations, and (3) wall considerations.

Wind-induced, outward-acting pressures act across four of the five surfaces of a rectangular building with a flat, or nearly flat, roof. Close attention must be paid to roof-to-wall connections, wall-to-wall connections, and wall-to-wall foundation anchorages in designs or evaluations of the building system or structure.

General uplift conditions on roofs are significant, and extreme uplift pressures at localized points can be critical, particularly roof overhangs, corners of flat roofs, eave lines, and ridgelines for gabled roofs. Elimination of overhangs can reduce local uplift pressures markedly, and parapets can further reduce these uplift concentrations. However, parapets must be designed as structural components or *they* will be inherent hazards.

Generally, metal decked roofs on open web steel joints are not heavy enough to resist uplift pressures without careful attention to anchorages. Equipment on the roof can be counted on as additional weight, but units must be properly positioned for maximum effectiveness, and anchored.

The largest single problem is that walls must be reinforced at panel ends and along eave lines to resist outward acting pressures. Local concentrations of outward acting pressures require additional reinforcement at wall corners.

PART III: WIND EFFECTS ON SYSTEM OPERATION

With few exceptions, buildings should not be oriented for an alleged "prevailing wind" to assist ventilation and air conditioning system operation. Even if the wind should prevail 80% of the time, which is seldom the case, the systems should perform adequately the rest of the time, regardless of wind direction. Such performance is essential for heat relief and contaminant control.

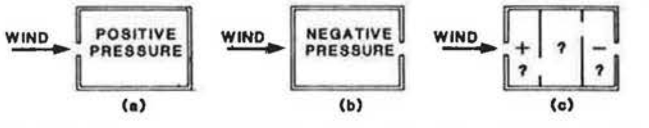


Fig. 10 Pressures in Buildings Resulting from Wind. In (a), with Upstream Opening Only, Pressure Will Be Positive. In (b), with Downstream Opening Only, Pressure Will Be Negative. In (c), Pressures Will Be As Shown If Openings Are Equal in Shape and Area. With Unequal Openings, Pressures May Be Either Positive or Negative in Each Space, Depending on Relative Areas of Openings.

However, *heat rejection equipment* must be designed to operate at the highest efficiency for the maximum number of hours possible during the season or seasons for which the equipment is required. Thus cooling towers and similar equipment should be oriented to take advantage of prevailing wind directions, based on careful study of the meteorological data for the area and time of year involved.

PRESSURE CONDITIONS

A building with an upstream opening only will be under a positive pressure (Fig. 10). With a downstream opening, building pressures will be negative. A building with numerous partitions and openings will be under various pressures depending on the relative sizes of the openings and the wind direction. With larger openings on the windward face, the building will tend to be under positive pressure. The reverse will be true if the openings are smaller than those downstream.

Flow through a wall opening results from differential pressure, which results from external and internal pressures, both of which may be positive or negative. Such differential pressures may exceed 125 Pa (0.50 in. H_2O) during high winds. Because of the various supply and exhaust systems and openings, dampers, louvers, doors and windows, the building flow conditions which will exist are usually too complex for practical calculation. The opening and closing of doors and windows by building occupants add further complications.

For ventilation design, note that the envelope shapes indicated in Figs. 1-4 are relatively constant for a given wind direction, regardless of wind speed. However, the pressures imposed on the building surfaces (and in the cavities) do vary with wind speed, as shown in Fig. 5. Because the wind direction is not constant, and the wind is turbulent, the shapes of cavities will vary somewhat.

Natural, Mechanical Ventilation

With natural ventilation, wind may either augment or impede (and sometimes reverse) air flow through a building (Chapter 22). For large roof areas (Fig. 2), the wind may reattach to the roof downstream from the cavity and thus reverse natural ventilation discharging out of monitor or similar windows. These reversals can be avoided by using stacks, continuous roof ventilators, or other exhaust devices for which the flow is augmented by the wind.

Mechanical ventilation is also affected by wind conditions. A low pressure wall exhaust fan, 12.5 to 25.0 Pa (0.05 to 0.10 in. H_2O) may suffer drastic reduction in capacity. Flow may be reversed by wind pressures on windward walls, or its rate may be increased substantially when subjected to negative

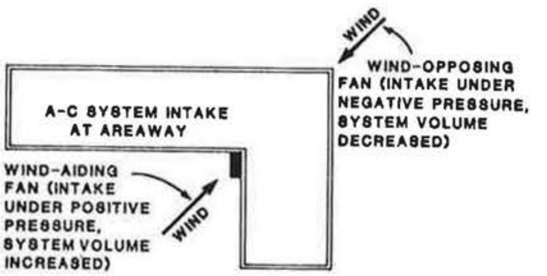


Fig. 11 Effect of Wind Pressure on Air-Conditioning System Volume, with Wind Blowing (1) Toward Intake Located at Areaway in Cove of *L*-Shaped Building, and (2) in Opposite Direction

pressures on the lee and other sides. Measurements on medium pressure air conditioning systems[15] (250 to 375 Pa) (1.0 to 1.5 in. H_2O) have indicated flow rate changes of 25% for wind blowing into intakes on an *L*-shaped building compared to the reverse condition (Fig. 11). Such changes in flow rate can cause noise at the supply outlets and drafts in the spaces served.[15]

For mechanical systems, the wind may be thought of as a "fan" in series with a system fan,[16] either assisting or opposing it. Where system stability is essential, the supply and exhaust systems must be designed for high pressures, around 750 to 1000 Pa (3 to 4 in. H_2O) to minimize unacceptable variations in flow rate. To conserve energy, the system pressure selected should be consistent with system needs.

Building Balance

Building balance is important in avoiding pressure or flow conditions which make doors hard to open, cause drafts, and prevent confinement of contaminants to specific areas. Although supply and exhaust systems of an area may be in nominal balance, wind may upset this, not only because of the changes in fan capacity, but also by superimposing infiltrated or exfiltrated air, or both, on the area (Fig. 12). The latter effects can make it impossible to control the environmental conditions. Where building balance and minimum infiltration are important, consider:

1. Fan system design for adequate pressure to minimize wind effects.
2. Controls to regulate flow rate or pressure or both.
3. Separate supply and exhaust systems to serve each building area requiring control or balance.
4. Doors (possibly self-closing) or double-door air locks to noncontrolled adjacent areas, particularly outside doors.
5. Sealing windows and other leakage sources and closing natural vent openings.

System volume and pressure control is described in Chapter 34, 1980 SYSTEMS VOLUME. Such 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, or fan speed control, or both. Some axial fans have controlled blade pitch.

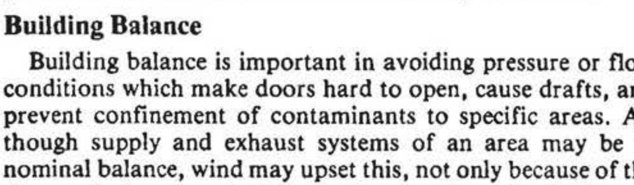


Fig. 12 Flow of Infiltrated and Exfiltrated Air, Caused by Wind Pressures, Superimposed on Air-Conditioning Flow in Otherwise Balanced Air-Conditioning System, Thus Destroying Environmental Control. Where Environmental Control is Particularly Important, Spaces Must be Airtight

Safe Hood Operation

Wind effect may imperil the safe operation of hoods. Supply (makeup) volume variations may cause disturbances at the hood faces or a lack of adequate makeup air. Volume surges, caused by turbulent wind conditions acting on the exhaust system, may cause momentary inadequate hood exhaust. If highly toxic contaminants are involved, such surging is unacceptable and the system should be designed to eliminate it as previously described. On low pressure exhaust systems, it is impossible to test the hoods under wind-induced, surging conditions. Such systems should be tested during calm conditions for safe flow into the hood faces, and then rechecked at high wind conditions by smoke tests.

Minimizing Wind Effect on Volume

Wind effect can be reduced by careful selection of the inlet and outlet locations. Wall surfaces are subject to a wide variation of pressures, both positive and negative (Figs. 1, 2, and 5), so wall openings should be avoided whenever possible. Where wall openings *are* used, these should *not* be near the building corners nor in coves formed by building wings (Fig. 11), and the systems should operate at a pressure which will adequately minimize wind effect. Low pressure systems and propeller fans should not be used with such openings unless the ventilation is nominal or for unimportant services such as ordinary storage areas.

The best inlet locations to minimize wind effect are within a cavity on the roof, where the pressure is always negative. On large roofs, the best locations are in areas where the wind flow has reattached (not near roof edges). Within a cavity the middle of the roof is the best area because the negative pressure there is small and generally is least affected by changes in wind direction (Fig. 5). Either vertical or horizontal (mushroom) openings may be used. On large roof areas where the intake may be outside the roof cavity (and the wind flow has reattached), mushroom or 180° gooseneck designs should be used to minimize impact pressure from wind flow. The frequently used 135° gooseneck or vertical louvered openings are undesirable for this reason and for rain protection.

Generally exhausts, whether discharging heated air only, nominal office exhaust, or contaminants (toxic, odorous, or nuisance), should discharge vertically through stacks, *above the cavity*. Horizontal, louvered (45° down) and 135° gooseneck discharges are undesirable even for simple heat removal systems because of the possibility of wind effect. The 180° gooseneck for systems handling hot air may be undesirable also because of air impingement on tar and felt roofs. Vertical discharging stacks (except near a wall) are subjected to negative pressure only, created by wind flow over the tip of the stack. Outlets or stacks should be mounted back from roof edges because of the wind and pressure extremes which occur along these areas.

BUILDING AND BUILDING AREA PRESSURE AND FLOW CONTROL

In air-conditioning and ventilation systems for a building containing airborne contaminants, the proper direction of air flow in a space is toward the contaminated areas. Air flow 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 air flows in the spaces in conjunction with the exhaust systems in the laboratories, with differential pressure instrumentation to control the air flow. See 1980 SYSTEMS VOLUME, Chapter 34.

Air handling systems can be designed to maintain the necessary air flow but corridors may vary from atmospheric pressure. To minimize this, a reference probe can sense the outdoor static pressure. The tip of this probe should be designed to be unaffected by velocity pressure. The differential pressure measured between the corridor and the outside may then signal a controller to increase or decrease air flow to the corridor. Unfortunately, it is difficult to locate an external probe in a position in which it will sense only external static pressure. High wind velocity and resulting pressure changes around entrances can cause great variations in pressure, so the probe, or multiple probes connected to one header, should be placed to measure (as nearly as possible) the average static pressure around the corridor entries.

The control of pressure differential for a room adjacent to a corridor can be accomplished by using the corridor pressure as the reference. *It is not practical to control the pressure differentials of rooms with respect to the outside,* even during periods of relatively constant wind velocity and pressure. Even for a fixed wind direction, the pressure will vary in both horizontal and vertical directions on the building surface (Fig. 5). A single pressure sensor can measure the outside pressure at one point only and this may not be representative of the pressures elsewhere.

INLET AND OUTLET DESIGN FOR WEATHER AND DUST PROTECTION

With the wind normal to the windward building wall (Fig. 1), air flows up and down the wall. For most one- and two-story industrial buildings, the flow will divide about halfway up the wall. The down flow creates turbulence which stirs up dust and debris. The upward flow on the upper half of a wall will carry rain drops *up* the wall during high winds.[16,17] Because of turbulence, rain may be carried horizontally on the roof or along the walls. Snow and fluff (dandelion and cottonwood) will drift into any system intake in quantity regardless of louvers or canopies, and such debris can quickly plug openings.

Rain does not fall straight down. From observation and climatology data,[17,18] fall angle is usually more than 15° from the vertical. During a typical storm, most of the rain volume falls during a relatively short time. This heavy rainfall is usually accompanied by high winds and resultant high rain angles. While the average rainfall angle may be modest, it is the high angle of fall during the heavy rain periods which is significant. Thus most cone caps used on stacks, 135° goosenecks, and 45° wall canopies or louvers *are far from rain tight.*

For maximum weather and dust protection, the following design guidelines are offered:

1. The best overall location for inlets is on the roof, back from the edge if contaminant discharges are properly designed to minimize reentry.

2. Where wall openings are used, they should be located high above the ground but not above the mid height of the wall. Areaway (sunken) and ground level openings should be avoided if possible but at least include coarse screens and prefilters to minimize rain, dust, snow, and debris (organic and inorganic). The openings should be kept away from building corners because of the turbulent flow and pressure conditions.

3. Inlet goosenecks should be the 180° type and wall canopies should be the 90° type. Where wall louvers are used, these should be deep, about 150 mm (6 in.), to reduce rain entry, and the first system compartment should be provided with a drain. Rain "hooks" on the louver blades may reduce rain intake and stiffen the blades.

4. Exhaust stacks can be made nominally raintight by the designs in Fig. 13.

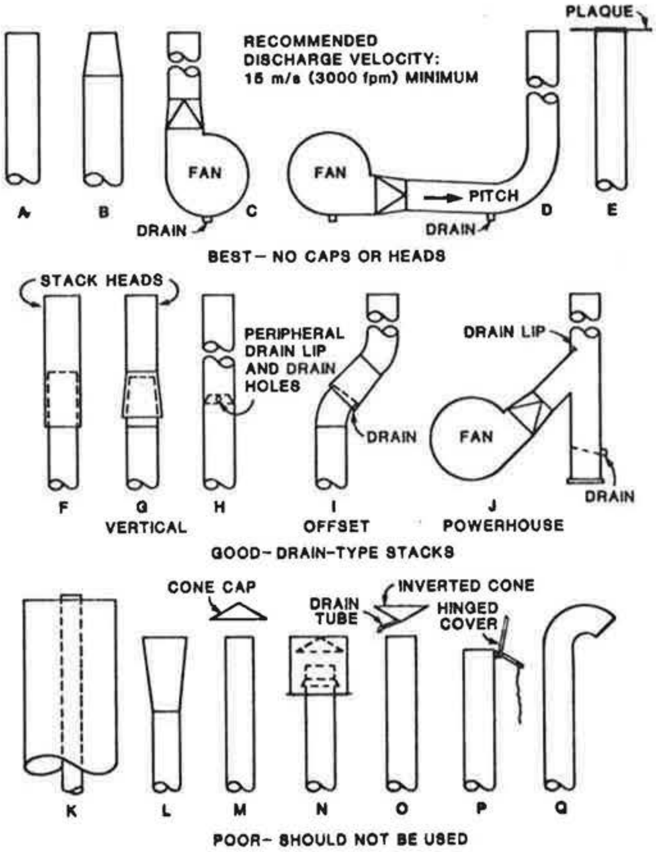


Fig. 13 Stack Design to Provide Vertical Discharge and Rain Protection

PART IV: DESIGN TO MINIMIZE REENTRY

Areas of concern caused by building and equipment exhaust recirculation are:

1. Health hazards and nuisance odors resulting from industrial processes, and from operation of laboratories, medical facilities, and restaurants.

2. Reduction in capacity of air-conditioning and heat rejection equipment (cooling towers and air-cooled condensers).

3. Accelerated corrosion of equipment.

VENTILATION AND AIR-CONDITIONING INLETS AND OUTLETS

Inlets should be located to minimize reentry from contaminated sources, including heat, humidity, and dust which can materially affect system loads. In warm weather, entry of water vapor from a cooling tower can add materially to the load of air-conditioning systems, and can reduce the effectiveness of heat-relief ventilation systems. In cold weather, it can cause freeze damage to equipment and block intake grilles

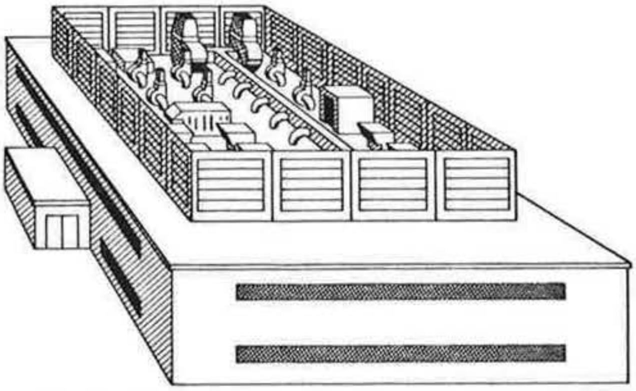


Fig. 14 Use of Architectural Fences Represents Very Poor Design

and filters by ice, greatly reducing system performance. It is also important that inlets not be near hot exhausts discharging horizontally or deflected down, *nor be near plumbing vents.* Of more importance is the need to locate contaminated exhausts carefully. Codes requiring inlets to be a specified minimum distance, such as 6 m (20 ft) from an exhaust are unrealistic. Much greater distances are required where the exhaust discharge is not properly designed.

Supply inlets and exhaust outlets should not be located within enclosures or architectural screens (Fig. 14). These are provided on some buildings to improve appearance. They hold building exhausts in their cavities, increasing reentry of contaminated air and odors, which may also cause excessive plugging and corrosion for the finned surfaces of heat rejection or exchange coils. Restaurant kitchen hood exhausts are particularly destructive in this respect.

Frequent changes and additions are made to buildings, particularly industrial and laboratory buildings. Initially satisfactory inlet and exhaust conditions can be the source of future unacceptable contaminant or odor problems.

STACK DESIGN

Contaminated effluents should first be reduced to reasonable or legal rates or concentrations by collectors, scrubbers, or a change of process if necessary. The remaining effluents must then be discharged into the atmosphere with sufficient dilution and dispersion to provide both acceptable minimum reentry into the building and minimum air pollution of adjacent areas. For many systems, typically laboratory exhausts, the concentrations of contaminants may normally be very low during most operating times, but higher concentrations, which must be dispersed, may be experienced for short periods of time. Some primary stack design considerations are:

1. Stack height should be the maximum practical, subject to the requirements for dilution, dispersion, and the elimination of unacceptable reentry through building openings. A method for estimating stack heights for flat-roofed, rectangular buildings is shown in Fig. 15 and Example 1, which have been modified from Ref 19, with the length scale factor R replaced by $(A)^{0.5}$. The minimum stack height selected should cause the flow of the complete plume to be above the building inlets, the building cavity (elevation Z_1), and, for areas where the flow has reattached to the roof, the downstream high turbulence zone (elevation Z_2). If such stack height is not practical, the minimum allowable distance between the stack and the inlet can be estimated from Eq 11 or 12, or the method of Ref 20, and be confirmed by full-scale tests (existing buildings) or model smoke and dilution tests.

Flow conditions should be checked for wind directions both parallel and perpendicular to the long dimension of the building. Future supply and exhaust systems, which may not be ideally located, should be considered when selecting stack location and height. The stack height estimate may even be based on an inlet located at the far end of the roof, point *A* in Fig. 15, even though inlets close to a roof edge are undesirable.

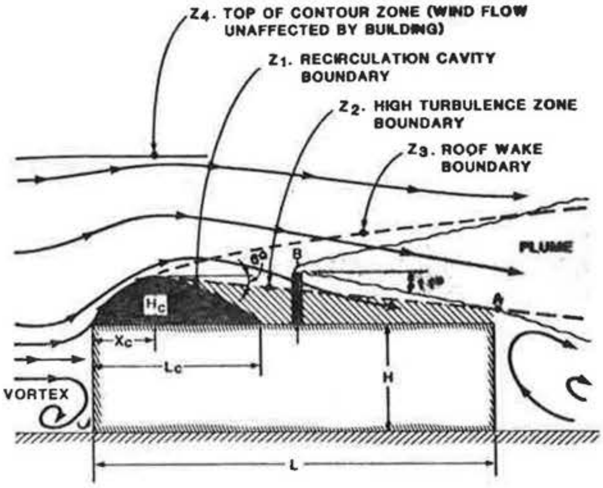


Fig. 15 Centerline Wind and Stack Flow Patterns Are Applicable to Simple Rectangular Block Buildings with Wind Perpendicular to Upwind Face. To Prevent Reentry from Stack to Inlet, Expanding Stack Plume Must Be above Maximum (Centerline) Heights of Cavity and Following High Turbulence Zone Boundaries, Z_1 and Z_2

For many one- or two-story industrial or laboratory buildings, stacks 5 m (16 ft) in height have been found adequate for discharging above the roof cavity, with acceptable dilution at inlets for contaminants of moderate toxicity or odor perception. The greatest contaminant concentration is along the plume centerline. The fringes of the plume are highly diluted by the induction and turbulent air of the plume expansion.

Where the effluents are highly toxic or have odor perception at very low concentrations (such as hydrogen sulfide), it is probable that this is a potential neighborhood pollution problem, and the discharge should be above the contour zone (elevation Z_4) where wind flow is unaffected by the building. Stack heights of 30 to 45 m (100 to 150 ft) above the roof have been commonly used for this service.

Example 1: For the building of Fig. 15, determine the height above the roof of a stack necessary to prevent reentry into the building inlets. In Figs. 1, 2, and 3, the dimensions are approximate because of turbulent wind flow. Where the height and width of the building are within a factor of eight of each other (Table 1):

H = height $\quad W$ = width $\quad A = H \cdot W \quad A^{0.5}$ = scale factor

$H_c = 0.3(A)^{0.5} \quad X_c = 2.27\,H_c \quad L_c = 1.2(A)^{0.5} \quad Z_4 = 1.5(A)^{0.5}$

Draw the building side elevation to scale and establish the values for H_c, X_c, and L_c. Draw vertical lines at the proposed stack locations and at the air inlet farthest from the stack. (To account for unknown future inlet installations, locate the inlet line near the roof edge, point *A*.) Draw a vertical line at length X_c and establish the maximum cavity height. Draw the Z_2 boundary line, extending it from the maximum cavity height at a down slope of 6° or 1:10.

At the inlet location selected, indicate its proposed height above the roof. If this is above Z_2 (or beyond its intersection with the roof), draw a line back from the inlet location to the stack using an up slope of 11° or 1:5. If the inlet is below Z_2, extend the vertical line at the inlet to its intersection with Z_2 and run the plume boundary line back to the stack line as above. This establishes the minimum stack height, which should be increased about five diameters if a cap is installed (see item 8 below) or if the discharge velocity is low (stack to wind velocity ratio $R<1.5$, see item 3 below and Fig. 16), to compensate for downwash along the stack.

2. High stack discharge velocity and temperature increase plume

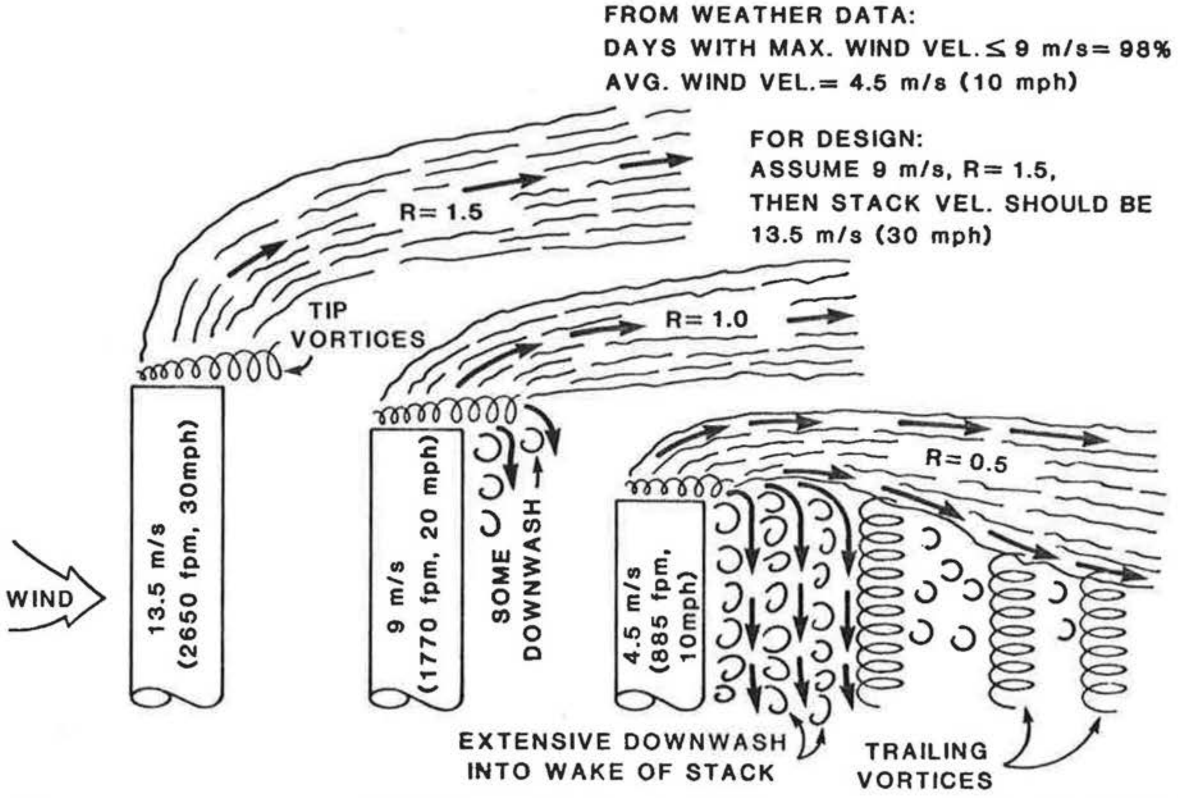


Fig. 16 Effect on Stack Discharge for Several Values of *R* (Stack to Wind Velocity Ratio). *R* Should Be 1.5 Minimum to Prevent Downwash along Stack

height and thus the effective stack height. This is very important for stacks for large central station boilers. It is of minor importance for small stacks which have low effluent momentum, typical of most industrial, laboratory, and commercial buildings, because of the overpowering wind effect.

3. Wind flow over stacks creates negative zones and eddies behind the stacks in the same manner as flow around buildings (Fig. 16, Ref 21). Low stack discharge velocity will permit the effluent to be drawn into the stack eddy zone and may cause downwash as much as six stack diameters. This *reduces* the effective stack height and may cause the effluent to enter the building cavity even though the discharge may be above the cavity.

The stack exit velocity (Fig. 16) should be at least 1.5 times the wind velocity ($R = 1.5$) to keep stack downwash to a minimum.[21, 22] For heating boilers or other systems which may operate over a wide range of capacity, a higher stack velocity, for instance 20 m/s (4000 fpm), might be selected to obtain a reasonable value of R at reduced loads. Plaques at the stack tip similar to Fig. 13e have been used on boiler stacks to help clear the flue gases from the stack eddies, but may provide only marginal improvements, so the design should be tested before use.

Often it is desired to blow condensed moisture out of the stack. The terminal velocity of a large rain drop is about 10 m/s (2000 fpm).[23] A stack velocity of about 13 m/s (2560 fpm) to allow for the lower velocity near the skin of the stack, will not only prevent condensed moisture from draining down the stack, *it will also keep rain out of the stack*. Where condensed moisture is corrosive or unsuitable for blowing out of the stack (solvents, for example), the stack should be sized for very low velocity, 5 m/s (1000 fpm), and a drain provided at the base. The stack tip should have a converging cone (Fig. 13b) to provide high velocity discharge.

4. High velocity stack discharge is a very poor substitute for stack height. It has been noted that a stack to wind velocity ratio of at least 4:1 would be required to discharge the effluent partially out of the cavity for a flush stack (terminated at roof level) (Ref 11, par. 6.4, and Fig. 12). The equivalent stack velocities would be in the range of 36 to 41 m/s (7000 to 8000 fpm), usually unacceptable from an energy standpoint alone.

5. A stack should not be provided with a large enclosure, with the tip flush with the top of the enclosure (Fig. 13k). This would be similar to a flush discharge on a roof, nullifying the beneficial effects of velocity and temperature, and causing unacceptable downwash. Where enclosures are necessary, the actual stack should extend above the eddy zone or cavity of the outer enclosure.

6. Stacks should be located on the highest roof of the building, where possible. They should not be located on a low roof or the ground unless tall enough to terminate above the adjacent roof cavities (as would be required by a roof-mounted stack) and to discharge clear of the detrimental wakes of nearby structures. Flow studies by model testing may be desirable, or the installation should be checked by smoke tests.

7. The best stack shape is a straight cylinder (Fig. 13a, b). Converging nozzles at the stack top (Fig. 13b) can provide adequate discharge velocity where the main stack velocity is low because of condensation or friction considerations.

8. Avoid stack caps which deflect the effluent down or drastically reduce the necessary vertical, high velocity discharge (Fig. 13 l-q). For systems which operate continuously and have discharge velocities in excess of 10 m/s (2000 fpm), rain will not enter the stack. Refer to item 3 above. A design velocity of 13 m/s (2560 fpm) is suggested.

Patented rain caps for stacks are used frequently with gas- or oil-fired furnaces and package-type ventilation units. These units should be located with caution to avoid reentry. Because they deflect the effluent down, stack caps should not be used for contaminant exhaust systems, including stacks for large boilers. See Part I and 1979 EQUIPMENT VOLUME, Chapter 26.

For intermittently operated systems, some weather protection may be needed if the down time is appreciable. Nominal rain protection can be provided by drain-type stacks (Fig. 13f, g, h), which provide better protection than the usual cone cap. Complete rain protection is provided by the designs in Fig. 13c, d, i, j.[24]

Standard cone caps (2/3-diameter gap at the stack top) are not efficient for eliminating rain. The cap on a 300-mm (12-in.) diameter stack passed 16% of all rain and as much as 45% during individual storms.[25] When the cap is fitted closely, the effluent is deflected down sharply and exit pressure loss is needlessly high.

Appearance is a problem of stack design. The problem has often been solved by careful selection of type of stack, color, and location. The problem is much more difficult if a large number of stacks is proposed and the plant or laboratory building is located where there may be much concern with aesthetics. Large central contaminant exhaust systems simplify the problem. These should always be used where safe and practicable. Such systems will dilute intermittent bursts of contaminant from a single hood or collecting station. In some instances, such as for perchloric acid exhaust hoods, separate systems are mandatory. Contaminant nature, recommended industrial hygiene provisions, and applicable codes must be considered.

A large central exhaust system is more reliable and readily maintained than a number of small systems. Where safety is particularly important, two fans in parallel have been installed to provide some exhaust during an outage of one fan, and alarms have been provided in case of fan failure.

HEAT REJECTION EQUIPMENT

Cooling towers and similar heat rejection devices are very sensitive to air flow around buildings. Such apparatus is frequently roof-mounted, with intakes close to the roof where air may be considerably hotter and at a higher wet-bulb temperature than the surrounding air, which is free of the roof's influence. This can reduce the capacity of cooling towers and air-cooled condensers.

Small cooling towers often take air in one side and discharge heated, moist air horizontally from the other side. Larger equipment usually discharges the hot air vertically upward.

For horizontal air flow cooling towers, or similar fan apparatus, changes in wind direction and velocity caused by immediately adjacent building configurations, can drastically reduce equipment performance by reducing air flow rate. Performance of cooling towers is almost directly proportional to the air flow through the equipment.

Even more serious than reduction in air flow rate to such devices is "recirculation." If some cooling tower's discharge air is forced back into its inlet, the recirculation of moist air raises the inlet wet-bulb temperature, which markedly reduces performance. Local disturbance of air flow by buildings or other obstructions upstream, by architectural equipment enclosures such as walls with air inlet louvers, by structure which blocks air flow upward, or by a close downstream obstruction, can all cause recirculation. Proper functioning of heat rejection equipment requires minimal recirculation, regardless of wind direction and speed. Thus it may be necessary to extend the vertical discharges of this equipment.

CORROSION

Reentry of contaminated exhaust can cause considerable corrosion of mechanical and building equipment, such as cooling towers, heating and cooling coils, and sheetmetal work. It has been a source of severe product corrosion in manufacturing plants, particularly electrical and electronic.

PART V: TESTING—PHYSICAL MODELING AND FULL-SCALE MEASUREMENTS

Air flow around buildings is so profoundly affected by geometrical features that mathematical or empirical generalizations are not sufficiently precise for accurate determination of local mass, momentum, and heat transfer for most applications.[4] Determination of wind effects, particularly pollutant concentration and pressure distributions around buildings, can commonly be obtained for specific cases by testing. Data by measurements on small-scale models through physical modeling in wind tunnels or water channels can provide information for design prior to construction and an economical method of performance evaluation for existing facilities. Full-scale testing is essential to verify data derived from physical modeling and from real time monitoring of operating facilities.

Detailed accounts of physical modeling, field measurements, and applications to engineering problems resulting from atmospheric flow around buildings are available in the Proceedings of Conferences on Wind Engineering (see Bibliography).

PHYSICAL MODELING

Small-scale modeling will yield quantitative data on flow over buildings, pressure distributions, and concentration distributions in good agreement with corresponding full-scale phenomena provided three sets of similarities are approximated with sufficient accuracy.[4, 26, 27]

Similarity Criteria

These similarity sets are as follows:

1. Similarity of the natural wind.
2. Geometrical similarity of buildings and topography.
3. Kinematical and dynamical similarity of source effluents.

Simulation of the natural wind requires that an adequate physical model reproduces flow characteristics of the atmospheric boundary layer[28] (the lowest layer of the atmosphere up to a height of 300 to 500 m or 1000 to 1600 ft, where effects of surface drag disappear). Because of thermal stratification, stability of the atmospheric boundary layer ranges from stable to neutral to unstable at most locations during a clear day. A model capable of simulating all states of the atmospheric boundary layer must provide for vertical variations of fluid density by either vertical temperature or concentration gradients. In most applications, however, adverse wind effects are the result of strong winds with mean velocities in excess of 10 m/s (33 ft/s) at an elevation of 10 m (33 ft). During strong winds, and in the mixing layer over urban areas (the lowest 100-150 m or 330-500 ft layer), intense mechanical mixing inhibits development of thermal stratification and results in neutral or near neutral stability—an adiabatic lapse rate of approximately $-1°C/100$ m (-1 F/182 ft). Small-scale physical modeling of this important case can be achieved by generation of a turbulent boundary layer with a fluid of uniform density in a wind tunnel or water channel.

The requirements for "exact" similarity in *neutral flow* are:

1. Geometrical similarity of surface roughness, buildings, and topography for upwind fetch.
2. Equality of the ratio of the boundary-layer depth to roughness length.
3. Equality of Reynolds numbers, Re.
4. Equality of Rossby numbers, Ro.
5. A longitudinal pressure gradient approximately equal to zero.

The most convenient and versatile flow arrangement for approximating these requirements is illustrated in Fig. 17. Since a nominal value for the atmospheric boundary-layer thickness δ is approximately 400 m (1300 ft), the desired value of δ_m (subscript m refers to the model) for a typical model-prototype length ratio of 1:400 would be 1 m (3.3 ft). Reynolds number equality and Rossby number equality can-

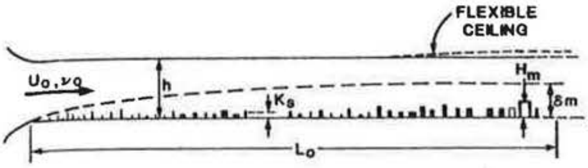


Fig. 17 Long Test-Section Wind Tunnel ($L_o/h>12$) for Natural Development of Boundary-Layer Characteristics at Site

not be achieved for model and prototype in practice because the length ratios must be small (1:200 to 1:500). However, in spite of this, excellent approximations to "exact" similitude are attainable.[4, 27, 28] Pressure drop in the flow direction can be adjusted to zero in a closed duct by small adjustments to the cross-sectional area; i.e., raising and lowering the ceiling, as indicated in Fig. 17.

Simulation of atmospheric boundary layers in the presence of *thermal stratification* introduces three additional requirements. For a common case in which stratification begins at ground level and gradually changes with height, these requirements are: (1) similar distributions of surface temperature, (2) equality of Richardson numbers, Ri, and (3) equality of Prandtl numbers, Pr.

All of these requirements can be met in an air flow facility properly designed for low speed operation with provisions for heating and/or cooling of the airstream and working-section floor. When the atmosphere has multilayer stratification, equality of model and prototype Richardson number and relative depth for each layer are required. The most common meteorological condition of this type is a shallow, slightly unstable layer (mixing layer) capped by an elevated inversion.[8]

Additional requirements must be met to obtain similar dispersion for effluents from sources on or near buildings. The principal requirements for source similarity are:

1. Equality of velocity ratio R (effluent emission speed V_e divided by mean wind speed at source height U_H).
2. Equality of densimetric Froude numbers Fr.
3. Equality of source to ambient density ratio ϱ_s/ϱ_a.

These conditions can be satisfied readily for source emissions that have either positive or negative buoyancy.[4, 28]

Flow Facilities

Physical modeling of the atmospheric boundary layer and the resulting flow and transport around buildings can be accomplished most accurately and economically in wind tunnels and water channels.[4] With very few exceptions, investigations of flow around buildings have been made in wind tunnels. Early studies, beginning in 1893, were made in small wind tunnels without boundary-layer development to simulate the natural wind.[29] By 1958 sufficient data were available from pressure measurements on small-scale models and their prototypes to conclude that simulation of the atmospheric boundary layer is essential for modeling of flow around buildings without gross error.[30, 31] This stimulated development of special low speed, long test-section, boundary-layer wind tunnels.[28, 32, 33]

Typical forms of wind tunnels that can satisfy the similarity requirements for atmospheric boundary-layer modeling either completely or partially are shown in Figs. 18 and 19. The most simple and common type is the open-discharge tunnel without heating and cooling provisions for establishment of thermal stratifications, as illustrated by Fig. 18. A return flow duct as shown in Fig. 19 is often added to develop flow free from external disturbances, and to reduce power requirements. When investigations of pollutant dispersion are made in a closed-circuit wind tunnel, tracer-gas concentrations in the ambient flow must be monitored. By adding heating and cooling of the test-section floor and in the return duct, the closed-circuit wind tunnel can be converted into a meteorological wind tunnel with capability for development of a wide range of thermal stratifications.

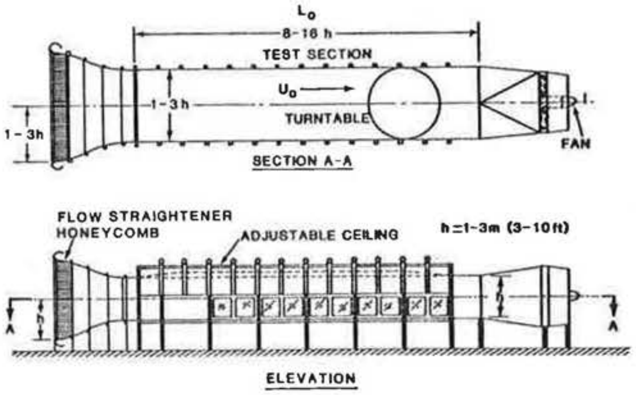


Fig. 18 Typical Open-Circuit Boundary-Layer Wind Tunnel

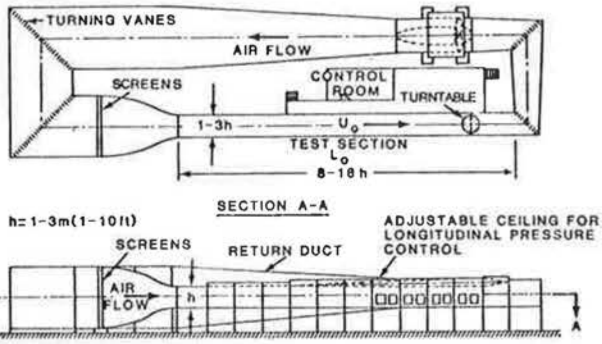


Fig. 19 Typical Closed-Circuit Boundary-Layer Wind Tunnel

When a long test-section wind tunnel is not available, a short test-section wind tunnel (length equal to 2 to 5 *h*, see Fig. 17) commonly used for aeronautical testing may be used for tests of flow around buildings.[34, 35] The necessary turbulent boundary layer is created by simulator systems at the test-section entrance, such as graded grids, fences, vortex generators, jets, spires, or screens. A combination fence and vortex-generator system,[36] a multiple-jet system,[37] or a counter-jet system[38] are satisfactory if surface roughness is adjusted properly. Surface roughness downstream from the simulator system must be equivalent to the roughness which, without the system, would have produced an equilibrium boundary layer with the same characteristics as those generated by the system. For investigations in which quantities sensitive to atmospheric turbulence are being measured, such as pressure fluctuations on building or pollutant concentration 10 source heights or more downwind of the source, boundary-layer simulation techniques should be used with caution.

Water can be used for the modeling fluid as well as air if an appropriate flow facility is available. Flow facilities may be in the form of a tunnel, tank, or channel. Water tunnels usually have short, small cross-section test sections compared to dimensions of the wind tunnels shown in Figs. 18 and 19. Hence, the atmospheric boundary layer cannot be simulated and only approximate qualitative information on flow around a building model can be obtained. Tanks of water with a free surface ranging in size up to that of a wind-tunnel test section have been utilized by towing a model (upside down) through the nonflowing fluid. A stable stratification can be obtained by adding a salt solution at the tank bottom. This technique does not permit development of a boundary layer, so it yields only approximate qualitative information on flow around buildings. Water channels can be designed to develop thick turbulent boundary layers for simulation of atmospheric boundary layers as described previously for a long test-section wind tunnel. An advantage of such a flow system is ease of flow visualization, but it is offset by greater difficulty in measurement of flow variables and concentrations. Stratification can be achieved by generating flow through the channel by a vertical array of horizontal line sources of water heated to different temperatures at different heights.[39]

Measurements

All tests of flow around buildings require (1) flow visualization for a qualitative description of overall flow characteristics, and (2) velocity measurements for quantitative detail. Pressure measurements are required for tests to determine wind effects on flow rates of intake and exhaust systems, infiltration and exfiltration rates, and interior building pressures. Investigations of pollutant dispersion and recirculation from exhausts to intakes involve both use of visual tracers and measurement of concentration distributions and temperature. Chapter 13 describes the fundamental aspects of instruments and measurement techniques for these purposes. Additional information on concentration measurements is presented in Refs 4, 9, and 10.

Flow visualization can be accomplished by introduction of point or line sources of smoke, or of a source of neutral bubbles inflated with helium, oil film, or tufts.[40] A convenient source of smoke is a small ball of cotton saturated with titanium tetrachloride. (Since a byproduct of this liquid with water in the air is hydrochloric acid, it must be used with great care.) Mineral oil vaporized in a nitrogen atmosphere provides another common source of smoke. Still or motion photography should be used to provide a permanent record of flow tests. Examples of recordings of pollutant transport over and around buildings by flow visualization techniques are given in Refs 4 and 10.

Mean air velocities and turbulent velocity fluctuations are commonly measured with hot-wire or hot-film anemometers. Information on turbulence (intensity and spectra) is useful when comparing model wind characteristics with atmospheric wind data to (1) check similitude, (2) evaluate diffusion coefficients near buildings, and (3) determine the downwind domain of influence (wake) for a building. When only pressures or concentrations are needed without relating them to local flow features, measurement of mean velocities is sufficient for a test. In these cases, a Pitot tube may be used to measure reference flow speeds and the mean velocity distribution within the approach-flow boundary layer. For good accuracy, flow speeds should be greater than 2 m/s (6.5 ft/s) when the Pitot tube is used.

Complete investigations of wind pressure effects on heating, air-conditioning, and ventilating systems require information on both mean and fluctuating pressures at building openings. Accordingly, the pressure measuring system should have good frequency response up to about 200 Hz.[34] A differential- pressure transducer of the bonded strain-gage type is commonly used for this purpose. The transducer is connected by tubing to a piezometer tap in the building and a static pressure sensor (Pitot tube) located in the undisturbed flow above the model building. The output may be recorded on magnetic tape for processing or digitized and processed on line to give mean, root-mean-square, and peak pressure coefficients.

When only mean pressures are needed, measurement can be made by connecting a manometer to a piezometer tap or Pitot tube. Direct reading of the manometer fluid-column heights gives a rapid determination of pressure difference if only a small number of locations are being studied. When pressures are needed at a large number of locations, a bank of manometer tubes may be used with photographic recordings of fluid-column heights.

Measurements of tracer-gas concentration are ordinarily limited to determination of mean values, since instrumentation for measurement of fluctuations is still in the developmental stage. The type of instrument used for this purpose depends primarily on the tracer used in the tests. A mass spectrograph (leak detector) can be used with helium, a Geiger-Mueller radiation detector with krypton 85, a gas chromatograph with hydrocarbons, and a titrator with ammonia. Aside from possible background concentration problems, the gas chromatograph and hydrocarbon tracers provide the optimum system. With this system, multiple sources may be studied simultaneously by using a different hydrocarbon tracer (e.g., propane, ethane, methane, butane) for each source.

The gas chromatograph determines the concentration of each tracer contained in a single sample. Visualization of surface areas on a building that are contaminated by pollutants released from a building vent or exhaust opening is often useful and revealing. A practical method for doing this is to coat the building model with latex paint that has been mixed with a pH-sensitive dye. For example, if congo red is mixed with a white latex paint, the surface is pink when wetted with a solution of hydrochloric acid. Release of ammonia from the source then causes a blue pattern to appear on surfaces contaminated by the effluent.

Design of Tests

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 building to be studied together with nearby neighboring buildings, and/or topographic features and thickness of the simulated atmospheric boundary layer. For tall buildings, the scale is often determined by the requirement that the ratio of boundary-layer thickness to building height (δ/H) should be approximately equal for model and prototype. Strong-wind boundary layers range in depth from 300 to 400 m (1000 to 1300 ft) for surroundings ranging from flat open terrain to suburbs of urban centers. Boundary-layer thicknesses in flow facilities have nominal depths ranging from 1 to 1.5 m (3 to 5 ft); therefore, H/H_m would ideally range from 200 to 400. However, use of a δ/H ratio 10 to 30% smaller than full-scale values does not lead to serious error.[31]

For complexes of low to moderately tall buildings extending over a wide area, such as an industrial plant or an urban center, the scale is usually controlled by test-section width. Most flow facilities available for testing purposes range in width from 2 to 4 m (6 to 12 ft). Hence, if interest were focused on an area of 500-m (1600-ft) radius, the scale could range from 1:500 to 1:250 depending on the test-section width. A large scale is usually desirable to meet minimum Reynolds number and Froude number requirements; therefore, a wide test section provides advantages for testing purposes. In general, the model at any section should be sufficiently small with respect to the test-section area that blockage is less than 10%.

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 at 22 1/2° intervals. This is easily accomplished by mounting a building and its near surroundings on a turntable. If only local wind information and pressures are of interest, testing at one wind speed with neutral stability is sufficient. This wind speed should be sufficiently large to give a building Reynolds number $(U_o L_o / \nu_o)$ in excess of 15 000. A wind speed U_o of 15 to 20 m/s (50 to 65 ft/s) is usually satisfactory for this type of testing and yields relative local wind speeds and pressure coefficients independent of the Reynolds number (wind speed). When circulation of air pollutants around a building is being investigated for a neutral atmosphere, the wind speeds U_o to be used in tests are determined by similarity requirements for the source characteristics.

Specifications of *source characteristics* must include, in addition to source geometry, the discharge speed V_e and the temperature and/or concentration of various components of the effluent to permit determination of effluent density. This information and meteorological data for the site determine a realistic range of values for the velocity ratio, R, (V_e/U_H) and the densimetric Froude number. Equality of model and prototype Froude numbers requires wind speeds less than 0.5 m/s (1.5 ft/s) for testing. However, larger wind speeds than given by the foregoing requirement may be needed to meet the minimum building Reynolds number requirement. Larger wind speeds are possible by using a density difference for the model effluent larger than the prototype difference.

For effluent with positive buoyancy, it is convenient to use a mixture of air and helium plus a tracer. A mixture of air and carbon dioxide plus tracer is ideal for a negatively buoyant effluent. Once the relationship between model and prototype flow speeds is known, the model source exit speeds V_e can be determined. These are necessary to preserve equality of the velocity ratio $R = V_e/U_H$, where the range of R to be used in testing is determined by (1) operational characteristics of the system that generates the source, and (2) meteorological characteristics of the site.

FULL-SCALE TESTING

While full-scale testing may seem the preferred method for assessing dilution of effluent from stacks and vents, it is often the most difficult and time consuming. Control of the most important variables isn't possible; namely, atmospheric conditions. To obtain a representative set of concentration data over a wide range of meteorological conditions may require months or even years. Visual tracers can often provide inexpensive, rapid indications of cavity size, source entrainment, and recirculation possibilities. A well planned set of concentration measurements is recommended for validation of results from numerical analysis or physical modeling studies. Used in this manner, a limited set of field test concentration data can be expanded through the use of physical or numerical modeling to include a wide range of meteorological conditions.

The experimental procedures used for full-scale testing are similar to those for a physical modeling study.[41, 42] A tracer gas is released from a vent or stack at a known rate after which concentrations of the tracer are measured at the desired locations in or outside the building. To document atmospheric conditions, wind speed, wind direction, and atmospheric stability measurements are required. Often a visual tracer is released to provide qualitative information on effluent dispersion processes. The main phases of field testing are discussed in the following paragraphs.

Tracers

At present the most frequently used tracer gas for full-scale measurements of mean concentrations is sulfur hexafluoride (SF_6),[43,44] a nontoxic, colorless, odorless, and tasteless gas that is nonflammable, noncorrosive, chemically inert, and has a high thermal stability.[45] It can be stored in liquid form under moderate pressures and can be easily dispensed from metal cylinders. Two gases with similar suitable characteristics are bromotrifluoromethane and octafluorocyclobutane.

Concentrations of these gases are detected by electron absorption detectors. SF_6 can be detected down to two parts per 10^{13}—still above the ambient background value of one part per 10^{14}. This makes SF_6 an ideal tracer for long- or short-range diffusion studies or when low source dilution factors are expected.

Tracer aerosols such as smoke plumes,[46] oil fogs,[47] spores,[48] dyes,[49] antimony oxide,[50] and fluorescent particles[51,52] have been used for both visualization and concentration determination. Orange Coast Guard flares provide an excellent visual tracer that can be photographed readily. The main problem with tracer aerosols is that they may exhibit atypical diffusion patterns because of losses from particle fallout or impaction.

Meteorological Data

The tracer concentrations measured must be combined with meteorological data for proper categorization and conversion to nondimensional forms. As a minimum, wind speed and direction should be measured (preferably at a height equal to the building height) along with temperature at two levels. After field testing, it is recommended that the wind station be left operating so that long-term statistics can be generated to predict the frequency of occurrence of worst-case dilution problems and to determine design stack exit speeds.

Design and Data Presentation

The design of each full-scale test may be different, depending on the results sought. It is generally advised that a consultant be obtained for the design and experimentation phases of the study. The basic study design steps are:

1. Decide on tracer gas (or visual tracer) to be used.
2. Estimate the maximum dilution expected to be measured.
3. Pick a tracer-gas analysis system which will measure the desired concentrations.
4. Design a tracer sampling device.
5. Designate sampling locations and tracer-gas release locations.
6. Pick instruments to monitor the total and tracer-gas release locations.
7. Install meteorological station(s).
8. Forecast the data for the desired atmospheric conditions (meteorological service).
9. Conduct field tests.

Depending on the results desired, the data may be displayed in two ways. The first would be the dilution ratio, $D = C_e/C$, and the second a concentration coefficient, K. See Eqs 5-9 and Fig. 6. To classify which conditions produce excess concentrations, the D or K values may be categorized by wind speed, wind direction, and stability.

LETTER SYMBOLS USED IN CHAPTER 14

A = a characteristic frontal area of building, m^2 (ft^2).
A_e = stack or exhaust vent area, m^2 (ft^2).

C = volume concentration of contaminant gas at roof level or at a ventilation intake.

C_e = volume fraction (concentration) of contaminant in vent gas.

C_{max} = maximum contaminant concentration at a fixed distance x from the vent or stack, along the plume centerline.

C_p = pressure coefficient, dimensionless.

$C_{p,z}$ = average pressure coefficient at height Z, based on velocity, U_Z.

$C_{p,H}$ = average pressure coefficient based on velocity U_H, at roof height.

$D = C_e/C$, gas dilution factor.

D_{min} = minimum dilution factor at a fixed distance r from the vent.

h = height or diameter of wind tunnel, m (ft) (Fig. 17).

H = height of building, m (ft).

H_c = maximum height of cavity or reverse flow region over building roof, m (ft) (Fig. 1).

H_m = height of model, m (ft) (Fig. 17).

K = concentration coefficient (Eq 5).

K_e = value of K at exhaust vent or stack exit.

K_{max} = maximum of K value at a fixed distance from the vent.

K_s = equivalent sand roughness of particle diameter.

L = building length in the wind direction, m (ft).

L_c = recirculation cavity reattachment length, m (ft) (Fig. 2).

L_d = diffusion length scale related to building size, m (ft).

L_o = tunnel test section length, m (ft) (Figs. 17, 18).

P_s = wind pressure on building surface, Pa (in. H_2O).

P_{se} = wind pressure on building surface, in. H_2O.

P_v = wind velocity pressure at roof level, Pa.

$P_{v,e}$ = wind velocity pressure at roof level, in. H_2O.

Q = volume flow rate of contaminant in stack gas, L/s (cfm).

Q_e = total stack or vent gas flow, L/s (cfm).

R = ratio of stack or vent exit velocity to wind velocity, V_e/U_H.

R_e = building Reynolds number $U_o L_o / \nu_o$.

r = shortest distance from vent to receptor on building surface, m (ft). (Note: vertical height from top of stack or vent should be added to horizontal distance.)

S = stretched string separation distance, exhaust to intake, m (ft).

U_H = wind speed at building roof height, m/s.

$U_{H,e}$ = wind speed at building roof height, mph (miles per hour).

U_o = tunnel mean wind speed, m/s (mph).

U_{ref} = wind speed at height Z_{ref} at which meteorological observations are recorded, m/s (mph).

V_e = stack or vent exhaust velocity, m/s (fpm).

W = building width perpendicular to the wind direction, m (ft).

X_c = distance from windward building face to location of maximum cavity height, m (ft).

Z = vertical distance above ground, m (ft).

Z_{ref} = vertical height at which meteorological observations are recorded, m (ft).

Greek Symbols

δ = atmospheric boundary layer thickness or height, m (ft).

δ_m = wind tunnel boundary layer thickness, m (ft).

ν = kinemetic viscosity of air, m^2/s (ft^2/s).

ν_o = kinemetic viscosity of air in wind tunnel, m^2/s (ft^2/s).

ϱ = air density, kg/m^3.

ϱ_e = air density, lb/ft^3.

REFERENCES

[1] D. J. Wilson: Contamination of building air intakes from nearby exhaust vents (*Final Report*, ASHRAE RP-136, January, 1976).

[2] D. J. Wilson: Contamination of air intakes from roof exhaust vents (ASHRAE TRANSACTIONS,, Vol. 82, Pt 1, 1976, p. 1024).

[3] E. S. Holdredge and B. H. Reed: Pressure distribution on buildings (*Summary Report to Department of the Army, Camp Detrick, Frederick, MD,* Texas Engineering Experiment Station, College Station, 1956).

[4] J. E. Cermak: Applications of fluid mechanics to wind engineering (*Journal of Fluids Engineering, Transactions of ASME,* Vol. 97, 1975, p. 9).

[5] G. F. Hamilton: Effect of velocity distribution on wind loads on walls and low buildings (*TP 6205,* University of Toronto, Ottawa, Canada, 1962).

[6] P. Sachs: *Wind Forces in Engineering* (Pergamon Press, New York, NY, 1972).

[7] F. A. Gifford: An outline of diffusion in the lower layers of the atmosphere (*Meteorology and Atomic Energy,* U. S. Atomic Energy Commission, Div. of Tech. Information, TID 24190, 1968, p. 65).

[8] *ASME Recommended Guide for the Prediction of the Dispersion of Airborne Effluents, 2nd ed.* (ASME, New York, NY, 1973).

[9] D. J. Wilson: Dilution of exhaust gases from building surface vents (ASHRAE TRANSACTIONS, Vol. 83, Pt 1, 1977, p. 168).

[10] J. Halitsky: Gas diffusion near buildings (ASHRAE TRANSACTIONS, Vol. 69, 1963, p. 464).

[11] J. Halitsky: Gas Diffusion Near Buildings (*Laboratory Report No. 63-3,* Department of Meteorology and Oceanograpy, Geophysical Sciences, New York University, NY, February, 1963).

[12] J. Halitsky: Gas diffusion near buildings (*Meteorology and Atomic Energy,* U. S. Atomic Energy Commission, Div. of Tech. Information, TID 24190, 1968, p. 221).

[13] R. E. Munn and A. F. W. Cole: Turbulence and diffusion in the wake of a building (*Atmospheric Environment,* Vol. 1, 1967, p. 33).

[14] D. J. Wilson: Effect of vent stack height and exit velocity on exhaust gas dilution (ASHRAE TRANSACTIONS, Vol. 83, Pt 1, 1977, p. 157).

[15] John H. Clarke: Air flow around buildings (*Heating, Piping and Air Conditioning,* Vol. 39, No. 5, May 1967, p. 145).

[16] T. F. Houlihan: Effect of relative wind on supply air systems (ASHRAE JOURNAL, Vol. 7, No. 7, July 1965, p. 28).

[17] S. A. Changnon, Jr., and R. A. Jones: Weatherproofing the building—effect of wind-borne rain on weatherproofing (*Building Research,* November-December 1964, p. 8).

[18] S. A. Chagnon, Jr.: Selected rain-wind relations applicable to stack design (*Heating, Piping and Air Conditioning,* Vol. 38, No. 3, March 1966, p. 93).

[19] D. J. Wilson: Flow patterns over flat-roofed buildings and applications to exhaust stack design (ASHRAE TRANSACTIONS, Vol. 85, Pt 2, 1979).

[20] J. Halitsky: Estimation of stack height required to limit contamination of building air intakes (*Journal of American Industrial Hygiene Association,* Vol. 26, 1965, p. 106).

[21] R. H. Sherlock and E. A. Stalker: A study of flow phenomena in the wake of smoke stacks (*Bulletin No. 29,* Department of Engineering Research, University of Michigan, Ann Arbor, MI, March 1941).

[22] G. E. McElroy, C. E. Brown, L. B. Berger, and H. H. Schrenck: Dilution of stack effluents (*Technical Paper No. 657,* U.S. Bureau of Mines, Washington, DC, 1944).

[23] J. O. Laws and D. H. Parsons: Relations of rain drop size to intensity (*Transactions of American Geophysical Union,* Pt II, 1943, p. 452).

[24] How to design drain type stacks (*Heating, Piping and Air Conditioning,* Vol. 36, No. 6, June 1964, p. 143).

[25] John H. Clarke: The design and location of building inlets and outlets to minimize wind effect and building reentry of exhaust fumes (*Journal of American Industrial Hygiene Association,* Vol. 26, 1965, p. 242).

[26] J. E. Cermak: Nature of air flow around buildings (ASHRAE TRANSACTIONS, Vol. 82, Pt 1, 1976, p. 1044).

[27] J. E. Cermak: Aerodynamics of buildings (*Annual Review of Fluid Mechanics,* Vol. 8, 1976, p. 75).

[28] J. E. Cermak: Laboratory simulation of the atmospheric boundary layer (*AIAA Journal,* Vol. 9, No. 9, September 1971, p. 1746).

[29] I. Irminger: Experiments on wind pressure (*Proceedings of Institute of Civil Engineers,* Vol. 118, 1893-1894, p. 468).

[30] A. Bailey and N. D. G. Vincent: Wind pressures on buildings including the effects of adjacent buildings (*Journal of Institution of Civil Engineers,* Vol. 20, No. 8, October 1943, p. 243).

[31] M. Jensen: The model-law for phenomena in natural wind (*Ingenioren,* International Edition, Vol. 2, No. 4, 1958, p. 121).

[32] J. E. Cermak: Wind tunnel for the study of turbulence in the atmospheric surface layer (*Technical Report CER58JEC42,* Fluid Dynamics and Diffusion Laboratory, Colorado State University, Fort Collins, CO, November 1958).

[33] J. C. R. Hunt and H. Fernholz: Wind-tunnel simulation of the atmospheric boundary layer: A report on EUROMECH 50 (*Journal of Fluid Mechanics,* Vol. 70, Pt 3, 1975, p. 543).

[34] J. E. Cermak: Wind-tunnel testing of structures (*Journal of the Engineering Mechanics Div.,* ASCE, Vol. 103, No. EM6, 1977, p. 1125).

[35] J. A. Peterka and J. E. Cermak: Simulation of atmospheric flows in short wind tunnel test sections (*Technical Report CER73-74JAP-JEC32,* Fluid Dynamics and Diffusion Laboratory, Colorado State University, Fort Collins, CO, June 1974, p. 52).

[36] J. Counihan: A method of simulating a neutral atmospheric boundary layer in a wind tunnel (*AGARD Conference Proceedings,* No. 48, September 1969, p. 14.1).

[37] H. W. Teunissen: Simulation of the planetary boundary layer in the multiple jet wind tunnel (*UTIAS Report* No. 182, University of Toronto, Canada, June 1972).

[38] H. M. Nagib, M. V. Morkovin, and J. T Yung: On modeling of atmospheric surface layers by the counter jet technique (*Paper No. 74-638*, AIAA 8th Aerodynamic Testing Conference, July 1974).

[39] J. W. Clark: Laboratory investigation of atmospheric shear flows using an open channel (*Proceedings of AGARD Conference on Aerodynamics of Atmospheric Shear Flows*, 48, 1969, p. 15.1).

[40] W. Merzkirch: *Flow Visualization*, Academic Press, Cambridge, MA, 1974, p. 250).

[41] G.E. Start et al: Rancho Seco building wake effects on atmospheric diffusion (NOAA, Idaho Falls, ID, November 1977, p. 257).

[42] D. G. Smith: Influence of meteorological factors upon effluent concentrations on and near buildings with short stacks (Presented at the 68th Annual Meeting of the Air Pollution Control Association, Boston, MA, June 15-20, 1975).

[43] R. N. Dietz and E. A. Cote: Tracing atmospheric pollutants by gas chromatographic determination of sulfur hexafluoride (*Environmental Science and Technology*, Vol. 7, 1973, p. 338).

[44] A. Turk, S. M. Edmonds, H. L. Mark, and G. F. Collins: Sulfur hexafluoride as a gas tracer (*Environmental Science and Technology*, Vol. 2, 1968, p. 44).

[45] B. E. Saltzman, A. I. Coleman, and C. A. Clemons: Halogenated compounds as gaseous meteorological tracers: Stability and ultrasensitive analysis by gas chromatography (*Analytical Chemistry*, Vol. 38, 1966, p. 753).

[46] G. R. Hilst: The dispersion of stack gases in stable atmospheres (*Journal of Air Pollution Control Association*, Vol. 7, 1957, p. 205).

[47] M. L. Barad and B. Shorr: Field studies in diffusion of aerosols (*American Industrial Hygiene Association Quarterly*, Vol. 14, 1966, p. 153).

[48] J. S. Hay and F. J. Pasquill: Diffusion from a fixed source at a height of a few hundred feet in the atmosphere (*Fluid Mechanics*, Vol. 2, 1957, p. 299).

[49] E. Robinson, J. A. McLeod, and C. E. Lapple: A meteorological tracer technique using uranine dye (*Journal of Applied Meteorology*, Vol. 16, 1959, p. 63).

[50] G. F. Haines, Jr., W. C. L. Hemeon, and J. Cember: Method of tracing groundlevel distributions of stack gas emissions (*Journal of Air Pollution Control Association*, Vol. 8, 1958, p. 262).

[51] A. E. J. Eggleton and N. Thompson: Loss of fluorescent particles in atmospheric diffusion experiments by comparison with radioxenon tracer (*Nature*, Vol. 192, 1961, p. 935).

[52] R. K. Dumbauld: Meteorological tracer technique for atmospheric diffusion studies (*Journal of Applied Meteorology*, Vol. 1, 1962, p. 437).

BIBLIOGRAPHY

H. G. Acker: Stack design to avoid smoke nuisance (*Transactions of Society of Naval Architects and Marine Engineers*, Vol. 60, 1952, p. 566).

D. E. Allen and W. A. Dalgliesh: Dynamic wind loads and cladding design (*Paper 611*, National Research Council, Div. of Building Research, Ottawa, Canada, 1973).

P. J. Barry: Estimates of downwind concentration of airborne effluents discharged in the neighborhood of buildings (*Canadian Report*, AECL-2043, 1964).

F. B. Benson, J. J. Henderson, and D. E. Caldwell: Indoor-outdoor air pollution relationships—a literature review (*Pub. No. AP-112*, U. S. Environmental Protection Agency, August 1972).

C. F. Berghout: Field techniques used to determine height and exit diameter of a power house stack (*American Industrial Hygiene Association Quarterly*, Vol. 18, No. 3, September 1957).

J. A. Brink, Jr., and B. B. Crocker: Practical applications of stacks to minimize pollution problems (*Journal of Air Pollution Control Association*, Vol. 14, November 1964, p. 449).

N. Chien, Y. Feng, H. Wong, and T. Sino: *Wind-Tunnel Studies of Pressure on Elementary Building Forms* (Iowa Institute of Hydraulic Research, 1951).

L. W. Crow: The wind blows this-a-way and that-a-way (ASHRAE TRANSACTIONS, Vol. 82, Pt 1, 1976, p. 1039).

A. G. Davenport: Gust loading factors (*Journal of Structural Div. Proceedings*, ASCE, Vol. 93, 1967, p. 11).

A. G. Davenport: Rationale for determining design wind velocities (*Journal of Structural Div. Proceedings*, ASCE, Vol. 86, 1960, p. 39).

A. G. Davenport: Wind loads on structures (*NRC 5576*, National Research Council, Div. of Building Research, Ottawa, Canada, 1960).

A. G. Davenport and W. A. Dalgliesh: A preliminary appraisal of wind loading concepts of the 1970 National Building Code of Canada (*Technical Paper 405*, National Research Council, Div. of Building Research, Ottawa, Canada, 1971).

P. O. Davies and D. J. Moore: Experiments on the behavior of effluent emitted from stacks and/or near the roof of tall reactor buildings (*International Journal of Air and Water Pollution*, Vol. 8, 1964, p. 515).

R. L. Derham, G. Petersen, R. H. Sabersky, and F. H. Shair: On the relation between the indoor and outdoor concentrations of nitrogen oxides (*Journal of Air Pollution Control Association*, Vol. 24, 1974, p. 158).

P. J. Drivas, P. G. Simmonds, and F. H. Shair: Experimental characterization of ventilation systems in buildings (*Environmental Science and Technology*, Vol. 6, No. 7, July 1972, p. 609).

B. H. Evans: Natural airflow around buildings (*Research Report 59*, Texas Engineering Experiment Station, March 1957).

J. Halitsky: Air flow over buildings (ASHRAE JOURNAL, Vol. 7, No. 7, July 1965, p. 37).

J. Halitsky: Diffusion of vented gas around buildings (*Journal of Air Pollution Control Association*, Vol. 12, 1962, p. 74).

B. J. Held: Planning ventilation for nuclear reactor facilities (*Journal of American Industrial Hygiene Association*, Vol. 23, January-February 1962, p. 83).

E. S. Holdredge and R. H. Reed: Wind tunnel studies of pressure and velocity distribution (*Summary Report No. 2* to U. S. Army, Camp Detrick, MD by Texas Engineering Experiment Station, August 1957).

W. G. Hoydysh, R. A. Griffiths, and Y. Ogawa: A scale model study of the dispersion of pollution in street canyons (*Paper No. 74-157*, Presented at the 67th Annual Meeting of the Air Pollution Control Association, Denver, CO, 1974).

W. G. Hoydysh and P. C. Freudentahl: A study of dispersion of emissions from local space heating boilers (*Paper No. 73-121*, Presented at the 66th Annual Meeting of the Air Pollution Control Association, Chicago, IL, 1973).

M. Jensen and N. Franck: Model-scale tests in turbulent wind, Part I, Phenomena dependent on the wind speed (The Danish Technical Press, Copenhagen, Denmark, 1963).

M. Jensen and N. Franck: Model-scale tests in turbulent wind, Part II, Phenomena dependent on the velocity pressure, wind loads on buildings (The Danish Technical Press, Copenhagen, Denmark, 1965).

E. J. Kurek: Pressurization, convection and air flow inside buildings (ASHRAE JOURNAL, Vol. 7, No. 5, May 1965, p. 65).

T. Kusuda and P. R. Achenbach: Coincident summer weather characteristics of six selected cities in the United States (Institute for Applied Standards, National Bureau of Standards, Washington, DC).

J. E. Martin: The correlation of wind tunnel and field measurements of gas diffusion using Krypton-85 as a tracer (*Report of the Phoenix Memorial Project, Doctoral Thesis*, University of Michigan, Ann Arbor, MI, 1965).

R. N. Meroney and B. T. Yang: Gaseous plume diffusion about isolated structures of simple geometry (*Proceedings* of Second International Clean Air Congress, Washington, DC, December 1970, p. 1022).

R. N. Meroney and C. R. Symes: Entrainment of stack gases by building of rounded geometry (*Proceedings* of Conference on Air Pollution Meteorology, Raleigh, NC, CEP70-71RNM-CRS49, April 5-8, 1971).

R. N. Meroney and B. T. Yang: Wind-tunnel study on gaseous mixing due to various stack heights and injection rates above an isolated structure (Prepared for AEC Contract AT (11-1)—2053 Fallout Studies Branch, Div. of Biology and Medicine, U. S. Atomic Energy Commission, CER71-72RNM-BTY16, November 1971).

J. E. Minor, K. C. Mehta, and J. R. McDonald: Air flow around buildings as reflected in failure modes (ASHRAE TRANSACTIONS, Vol. 82, Pt 1, 1976, p. 1061).

R. W. Nolan: Design of stacks to minimize smoke nuisance (*Transactions of Society of Naval Architects and Marine Engineers*, Vol. 54, 1946, p. 42).

Y. Ogawa: *Effects of Building and Thermal Boundary Layer on Diffusion* (The Faculty of Engineering, Hokkaido University, Sapporo, Japan, December 1973).

F. Pasquill: *Atmospheric Diffusion* (D. van Nostrand and Co., New York, NY, 1962).

P. J. Pocock: Non-aeronautical applications of low speed wind tunnel techniques (*Mechanical Engineering Report, MA-243*, National Research Council of Canada, Ottawa, Canada, September 1969).

J. C. Rathburn: Wind forces on tall buildings (*Transactions of American Society of Civil Engineers*, Paper 2056, Vol. 105, 1940, p. 1).

E. W. E. Rogers and R. E. Whitbread: Industrial aerodynamics: A survey of research in the United Kingdom (*Aerodynamics Report 1200*, National Physical Laboratory, Teddington, England, 1966).

A discussion on architectural aerodynamics (*Philosophical Transactions*, Royal Society of London, Vol. 269, No. 1199, May 1971, p. 321).

C. Scruton: Wind effects on structures (*Proceedings* of Institution of Mechanical Engineers, Vol. 185, 1971, p. 301).

W. H. Shnyder: Similarity criteria for the application of fluid models to the study of air pollution meteorology (*Boundary Layer Meteorology,* Vol. 3, 1972, p. 113).

N. M. Standen, W. A. Dalgliesh, and R. J. Templin: A wind tunnel and full-scale study of turbulent wind pressures on a tall building (*NRC 13740,* National Research Council, Div. of Building Research, Ottawa, Canada, September 1971).

G. H. Strom and J. Halitsky: Important considerations in the use of the wind tunnel for pollution studies of power plants (*Transactions of ASME,* Vol. 77, 1955, p. 789).

B. T. Symes and R. N. Meroney: Gaseous dispersion into stratified building wakes (*AEC Report No. C00-2053-3,* U. S. Atomic Energy Commission, CER70-71BTY-RNM8, August 1970).

H. Thomann: Wind effects on buildings and structures (*American Scientist,* Vol. 63, May-June 1975, p. 278).

A. G. Wilson: Influence of the house on chimney draft (ASHRAE JOURNAL, Vol. 2, No. 12, December 1960, p. 63).

D. Wilson: Turbulent dispersion in atmospheric shear flow and its wind tunnel simulation (von Karman Institute for Fluid Dynamics, TN-76, 1971).

Wind effects on buildings and structures (*Proceedings of Conference,* National Physical Laboratory, Teddington, England, June 26-28, 1963, Vols, I and II, H.M.S.O., 1965).

Wind effects on buildings and structures (*Proceedings of International Research Seminar,* Ottawa, Canada, September 11-15, 1967, Vols. I and II, University of Toronto Press, Canada, 1968).

Wind loads on buildings and structures (*Proceedings of Technical Meeting,* National Bureau of Standards, Gaithersburg, MD, January 1969, U. S. Government Printing Office, 1971).

Wind effects on buildings and structures (*Proceedings of Third International Conference,* Tokyo, Japan, Sept. 6-11, 1971, Saikon Shuppan Co., Ltd., Tokyo, Japan, 1971).

Wind effects on buildings and structures (*Proceedings of Fourth International Conference,* Heathrow, England, September 1975, Cambridge University Press, London, England, 1976).

Wind loads on structures (*Proceedings of U.S.-Japan Seminar,* University of Hawaii, Honolulu, HA, Oct. 19-24, 1970).

Wind effects on structures (*Proceedings of Second U. S.-Japan Research Seminar,* Kyoto, Japan, University of Tokyo Press, Tokyo, Japan, 1976).

Wind effects on high-rise buildings (*Proceedings of Symposium,* Northwestern University, Evanston, IL, March 23, 1970).

Wind loads on structures (*Conference Report,* First U. S. National Conference on Wind Engineering Research, California Institute of Technology, Pasadena, CA, December 1970).

Wind engineering research (*Proceedings of Second U. S. National Conference,* Colorado State University, Fort Collins, CO, June 23-25, 1975).

Wind engineering research (*Proceedings of Third U. S. National Conference,* University of Florida, Gainesville, FL, Feb. 26-March 2, 1978).

Wind engineering (*Proceedings of Fifth International Conference,* Fort Collins, CO, July 9-14, 1979, Pergamon Press, New York, NY, 1979).

B. T. Yang and R. N. Meroney: Gaseous dispersion into stratified building wakes (*AEC Report No. COO-2053-4,* U. S. Atomic Energy Commission, CER70-71CRS-RNM11, August 1970).

J. R. Yocom, W. L. Clink, and W. A. Cote: Indoor-outdoor air quality relationships (*Journal of Air Pollution Control Association,* Vol. 21, No. 5, May 1971, p. 251).