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Chapter 11

TURBULENT DIFFUSION NEAR BUILDINGS

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11.1 INTRODUCTION

The concentration field produced by a source located near the ground in the vicinity of buildings can be significantly modified from that predicted by conventional diffusion formulae. Such formulae contain the implicit assumptions that the flow field has straight parallel streamlines, modest velocity gradients, and distributions of turbulence energy and length scales which result from surface features that remain unchanged over long distances. Near buildings the flow field becomes highly complex. Curved streamlines, sharp velocity discontinuities, and non-homogeneous turbulence disperse effluents in a complicated manner uniquely related to source configuration and building geometry.

At a time when good engineering practice for large pollutant sources is to propose stacks or vents 150 to 300 meters high, there is still a large use of mini-chimneys, flush vents, and architectural fences and enclosures on buildings to disperse effluents from small process activities. Such designs may result in problems ranging from offensive odors, loss of capacity of air conditioning equipment, product corrosion, blackening or deterioration of building facades to re-entry of toxic contaminants requiring evacuation of building areas. Scorer (1968, 1978) and Clarke (1969) quote numerous concrete examples. These include hotel kitchen exhaust vents which contaminate dining areas with offensive odors, loss of air conditioning capacity at supermarkets as a result of recirculation of 50 % of the air around air-cooled condensers, change of pH in cooling tower water by stack contamination, product corrosion at an electronics plant due to discharges re-entering the building through ventilation intakes, and blackening caused by apartment house incinerators. Finally, cases are noted where evacuation of large research complexes occurred during re-entry of toxic or noxious discharges from laboratory exhaust hoods.

Current wisdom concerning the best engineering practice for estimating turbulent diffusion from isolated chimneys or cooling towers is contained in chapter 10 of this text; whereas the detailed characteristics of disturbed boundary layers are discussed in chapter 7. Such of these materials as are relevant to predict concentrations of effluents from small industrial and fuel-burning installations, hospitals, parking lot garages, or petroleum or chemical processing facilities will also be reviewed in this section. Since relative source and receptor locations as well as each stack, ventilation, or building configuration is different, a general discussion is provided of wake/cavity dispersion aerodynamics in section 11.1. Diffusion near an isolated building, or a large structure surrounded by smaller features is considered in section 11.2; whereas dispersive perturbations associated with collections of buildings are reviewed in section 11.3. Since the automobile represents a primary source of hydrocarbons, carbon dioxide, and sulphate products, transportation associated diffusion problems have been considered in a separate section 11.4. Finally, hazard analysis for storage of cryogenic liquids and the production of various chemical products require the ability to predict the behavior of dense gas clouds resulting from chemical spills. The behavior of such buoyancy dominated dispersion may be found in section 11.5.

Actual concentrations in space or time may differ from values calculated here by a factor of two over the average or up to ten for individual puffs. Nonetheless such procedures as are proposed herein permit stipulation as to whether ambient air quality or health conditions are likely to be exceeded, met, or marginal. Once the locations where the highest concentrations are likely to occur are estimated, field or laboratory (wind tunnel) sampling at such locations should be considered unless the predicted concentrations are satisfactorily low. Consultation with a specialist in air pollution meteorology or building aerodynamics may be advisable if concentrations are marginal or the configuration is unique.

11.1.1 Isolated Versus Collection of Buildings

The behavior of gases emitted from stacks or vents after discharge to the atmosphere can be divided into three distinct phases. The first phase of a plume lifetime is determined by the specific properties of the discharge; i.e., the source location and its shape relative to surrounding objects, the source momentum and buoyancy. The second phase begins when excess momentum and buoyancy have been diluted to small values, and the disturbance of the air mass enclosing the gases is governed by turbulence and velocity perturbations generated by objects such as buildings in the vicinity. Finally, plume dimensions reach such a size that only atmospheric scale motions disperse the effluent; thus dispersal of all plumes of such size would be identical irrespective of the initial conditions. Phases 1 and 3 in the absence of significant structures is the subject of discussion in chapter 10. Phases 1 and 2 are the subject of this chapter.

Flow and dispersion in the vicinity of groups of buildings is often uniquely related to source and building configurations. It is normally difficult to generalize concerning such dispersive behavior analytically. Indeed, detailed examination of concentration magnitudes are best considered by physical simulation in large boundary-layer wind-tunnel facilities — the subject of chapter 13. Nonetheless some estimates are possible based on experience gained from a collection of field and laboratory programs. The flow around isolated buildings or large buildings standing among structures a good deal smaller (fossil fuel or nuclear power stations, air hangars, etc.) can be described with some confidence (see chapter 12). Thus an understanding of the flow around a single structure may permit optimum placement of gas sources and receptors to minimize hazard or discomfort.

11.1.2 Flow Structure Around an Isolated Building

The descriptions of the flow near structures are based upon laboratory observations of smoke patterns, neutrally-buoyant bubble-streak photographs, and oil-film analysis. Most of such data have been obtained in low speed aerodynamic or meteorological wind or water tunnels. Effective short stack or vent design requires a knowledge of the air flow over buildings; thus of particular importance are these factors:

(1) Flow over a building creates a positive pressure zone on the upstream side and negative zones on the roof, lee, and lateral sides. Although the pressure magnitudes change within these zones with windspeed for a given orientation, their relative magnitudes are unaffected (Akins et al., 1976).

(2) The zones of pressure induce bending of mean streamlines, secondary flow motions, separation and, subsequently, added turbulence as noted in Figures 11.1 and 11.2. Because the wind is turbulent, the contour regions of displacement or cavity will not be constant in size or shape (Clarke, 1969).

(3) When the wind is perpendicular to the upstream face of a simple cubical building, the eddy zone or cavity height will be about 1.5 times the building height and its length will be about 2.5 - 3 times the building height measured from the upstream face. If the building is made wider, the interference to flow increases, the cavity height increases, and the cavity length approaches 12 building heights. For long buildings or buildings immersed in turbulent shear flows, the flow may reattach to building roof or sides. A long wide building cavity may extend 7 building heights from the lee face (Hosker, 1979).

(4) Until recently the cavity region has been considered a closed recirculation zone bounded by the separation streamline rising from the upwind edge of the building roof. Pollutant gases could only entrain in or out of this region by turbulent transport across the surrounding shear layer. For finite width buildings it is now generally accepted that the streamline bounding the cavity is not the separation streamline, but that a streamline arising upwind impinges at the stagnation point downwind of the building. Thus the transfer of material in and out of the cavity region is not limited to turbulent transport across the classical cavity interface (Hunt et al., 1978). Rather material is advected into

the recirculation zone along the penetrating streamlines, and can be removed via rising spiral vortices developed behind the lateral edges of the building, entrainment into the surface-bound horseshoe vortex, turbulent transport, or, intermittently by a sudden collapse of the cavity region.

(5) When wind approaches a cubical building at some angle (~ 45^{O}) to the building face, two strong counter-rotating vortices are induced at the upwind roof edges which tend to reduce the cavity height and increase wake centerline velocities as they sweep high velocity fluid downward as shown in Fig.11.2. These vortices may persist up to 80 building heights downwind (Hansen and Cermak, 1975).

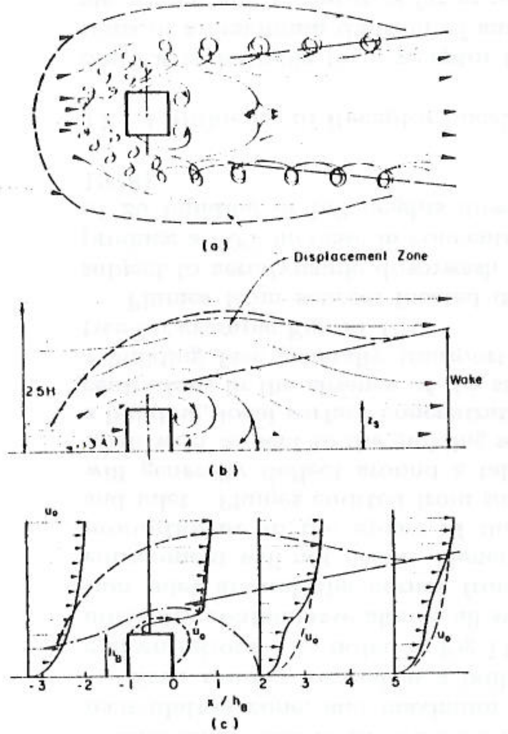


Fig.11.1 Fluids physics of a shear flow around a cubical building: 0^{O} orientation.

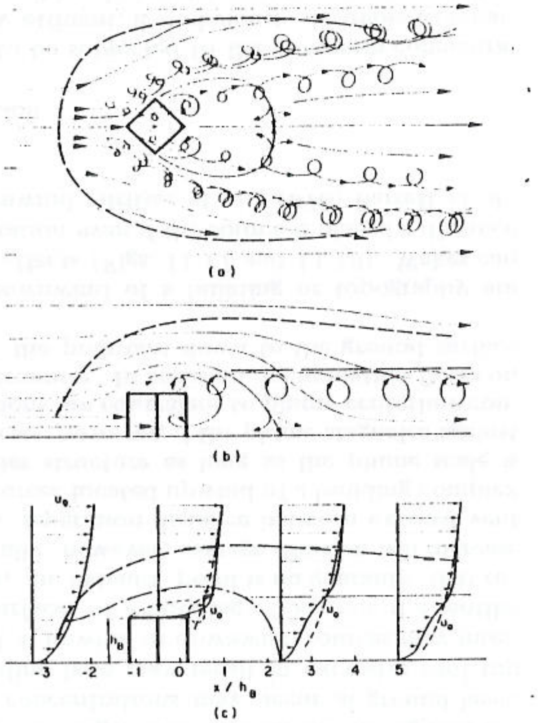


Fig.11.2 Fluid physics of a shear flow around a cubical building: 45^{O} orientation.

(6) For an isolated building the approach wind profile may induce a set of "horse-shoe" shaped vortices which wrap around the building base and trail downwind. Surface roughness or smaller auxiliary buildings will generally

disrupt these eddies; hence they often do not persist much beyond the cavity itself (Hatcher et al., 1977).

(7) Beyond the cavity region, aerodynamic downwash may persist for an extended distance bringing gases released above a building closer to the surface. Separation effects and secondary motions induced by the buildings also induce velocity deficits and turbulence excesses in the wake region which persists from 5 to 30 building heights downwind.

Penthouses, towers, air conditioning equipment, auxiliary buildings, and similar irregularities will change the flow conditions described above. Rounding a building or use of set-backs will decrease the heights of cavity, perturb reattachment locations, and modify dispersion patterns downwind of a building complex.

11.1.3 Influence of Source Location

All stacks and the building airflow itself may be affected by nearby buildings, other structures, and the variation of topography. However, if gases are emitted above the aerodynamic displacement zone noted in Figures 11.1 and 11.2,

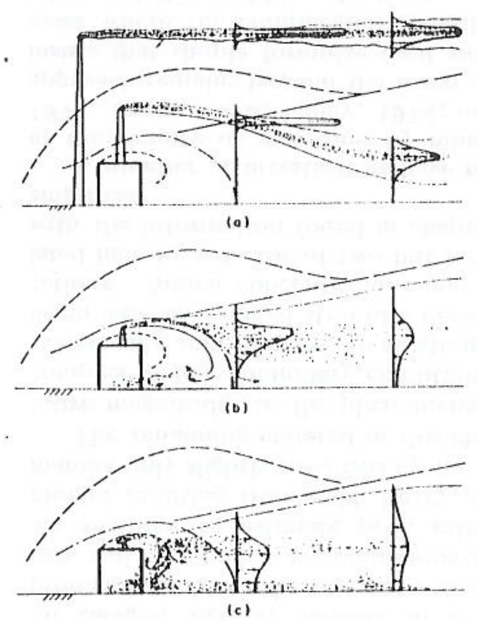


Fig.11.3 Short stack plume dispersion around a 0^{O} orientation cubical building

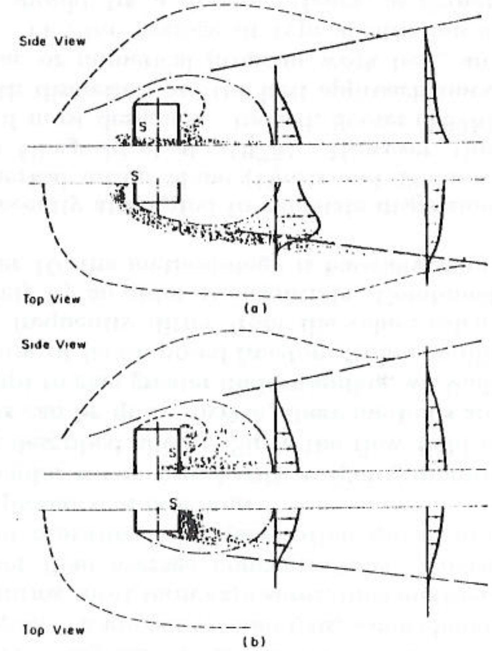


Fig.11.4 Flush vent exhaust dispersion around a 0^{O} orientation cubical building.

such effects are considered minimal. As a rough figure, the displacement effects are small for a cubical building above 2.5 building heights. Contaminants released within the displacement region but above the cavity streamline (see Fig. 11.3) may be subject to aerodynamic downwash which reduces the effective release height. Stack heights which do not extend above the cavity separation streamline but exceed the height of the roof separation region may result in medium-level gaseous concentrations at the building lee face; however, the majority of the effluents usually remain aloft. Flush vents on the building roof invariably result in low dilution levels which extend over the roof surface — sometimes back to the windward roof edge. Gases are mixed throughout the recirculation zone, and maximum concentrations may occur at ground level.

Even sources located at a building base may result in excessive roof top concentrations. As noted in Fig.11.4, upwind or downwind sources may intermittently contaminate almost all surfaces of a building. Location of a ventilation inlet around the corner from an exhaust point is no guaranty that re-entrainment will not occur. Generally, however, average dilution will increase proportionate to the square of the separation distance between exhaust vent and inlet. Plumes emitted from sources located upwind of a building complex will generally deflect around a taller structure as long as the plume scale is small with respect to the building scale; however, if the plume stagnates against a building, local surface concentrations are equivalent to plume centerline concentrations in the absence of the structure. In addition, recirculation flows on a building face generally transport the pollutant down to the ground surface (see for example Fig. 11.15).

Plumes from sources located downwind of a building or topography are subject to aerodynamic downwash effects (Figs. 11.17 and 11.13). Wakes can produce a 30% increase in concentration even if the source is placed a distance of 20 building or hill heights downwind (Britter et al., 1976; Barrett et al., 1978).

11.1.4 Influence of Receptor Location

Since it is desirable for a receptor to be subjected to the minimum concentrations or a maximum dilution of any effluent, it is obviously desirable to separate source and receptor as far as possible. In most cases one can expect that dilution will increase as the inverse square of the separation distance. There are, however, exceptions. Secondary motions within the cavity region may initially dilute pollutants; however, recirculation may result in a decay rate of the concentration proportional to the inverse square root of separation distance. Elevated plume concentrations will decrease with downwind transport; however, ground level concentrations may see an accelerated increase due to aerodynamic downwash to the surface.

11.1.5 Special Cases

Extreme hazards or special configurations require design rules developed specifically to analyze special cases. Transportation associated pollution problems have resulted in an entire set of literature dealing with dispersion in parking-lot garages, highway tunnels, or street canyons. It is best to discuss these problems qualitatively in a single chapter. Radioactive materials, some chemicals, and many odors are obnoxious during short term exposures; thus methods are required to estimate peak rather than average concentrations. Dense plumes resulting from cold, heavy, or moisture laden gases often spread in a manner only slightly modified by the presence of buildings.

The remaining material in this chapter is concerned with assigning quantitative magnitudes to the phenomena described above. Since the flow field is complex and the boundary conditions can be quite diverse, these methods are at best only approximate. In an attempt to gain greater understanding, we shall begin with an isolated structure because of its supposed freedom from complications. Actual concentrations may frequently differ from the values calculated here by a factor of two but rarely by an order of magnitude. Combined with the information found in chapter 10, the methodology is basically semi-empirical.

A number of investigators have recently attempted to calculate dispersion in the vicinity of structures by numerical means alone (Djuris and Thomas, 1971; Lantz, 1972; Laney, 1974; or Ukegushi et al., 1975). However, this approach remains beyond the reach of most designers. Indeed, Scorer (1978) insists that simple formulae used with discretion are the best approach since cases where the complicated formulae or numerical program work best, are often not the problem situations — i.e., the average or typical situation is not the constraint condition which should fix a design. Hence, as Scorer warns, do not let even these simple theories act as infallible knowledge in your design exercise.

11.2 DIFFUSION NEAR AN ISOLATED STRUCTURE

The Gaussian plume model discussed in section 10.3 is the foundation for most prediction schemes. It is basically an empirical model which has been found to agree with most data when the plume parameters are chosen in a specified manner (see section 10.3.2). As in most diffusion models, the variation of wind speed with height is neglected. Since dispersion considered in this section is at ground level either the velocity at source height, u_s, or a mean wind speed averaged over the expected depth of dispersion, $\overline{u}$, should be used in formulae. In order to generalize results to as wide a range of building configurations as possible, concentrations are expressed in terms of a dimensionless concentration coefficient, K, expressed as

$$K = \frac{CuL^2}{Q} \tag{11.1}$$

where C is local concentration, u is reference wind speed; L is a reference length scale (say the separation distance, s, or the building area cross-section normal to the wind, $\sqrt{A}$), and Q is the source strength in either mass, volume, radioactivity or odor units.

If volumetric units are used, the actual vent volumetric flow rate should be adjusted to an ambient temperature value. All units used herein are metric. Volumetric flow rate is in m^3/sec but if Q is expressed in kg/sec, then C units are kg/m^3. To convert this to g/m^3, multiply by 10^3. To convert to μg/m^3, multiply by 10^9. To convert the concentration of a gas to ppm, multiply by 24 x $10^6/m_o$, where m_o is source gas molecular weight. Alternatively, C in ppm may be found by expressing Q as $10^6(T_a/T_o)$ times the volumetric flow rate at the source in m^3/sec, where T_a is ambient temperature and T_o is source gas temperature. (The latter assumes, of course, that the molar specific heat capacities of source and ambient gases are nearly equal.)

11.2.1 Aerodynamic Downwash Conditions

As noted previously, if a short stack is in the near vicinity of a building roof, the emitting plume may be deflected to a lower effective stack height, h_e. To calculate this deflection, first estimate the aerodynamic stack height, h_A,

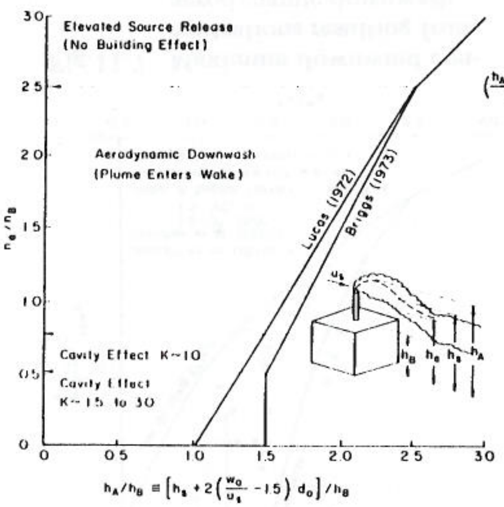


Fig.11.5 Effective stack height (when $h_B \lesssim w_b$ and plume is unheated).

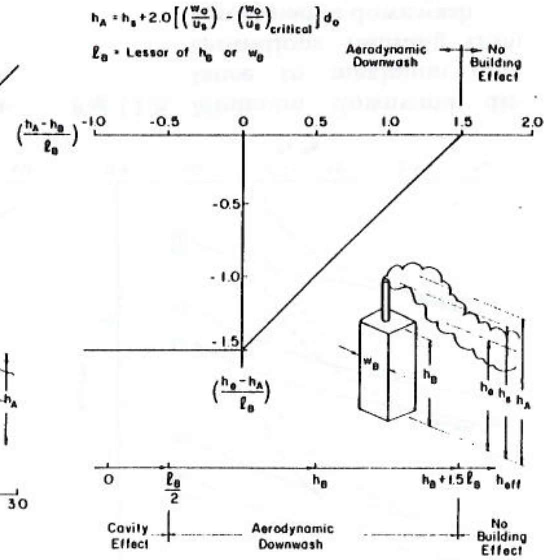


Fig.11.6 Effective stack heights (when $h_B > w_B$ and plume is unheated).

resulting from the combined effect of source height, h_s, and exit momentum, i.e.,

$$h_A = h_s + 2.0 \left[\frac{w_o}{u_s} - \left(\frac{w_o}{u_s}\right)_{critical} \right] d_o \qquad (11.2)$$

where critical velocity ratio values, w_o/u_s, are tabulated in section 10.6. Then, the effective stack height h_e is found as function of h_A and building shape. As a first approximation, Figs. 11.5 and 11.6 may be used which are based on the work of Lucas (1972) and Briggs (1973) who examined empirical correction methods together with experimental data on airflow around buildings. For a cubical or squat building where the building height is the minimum upwind face dimension, the effective stack height, h_e, may be estimated directly from Fig. 11.5. If the building is taller than it is wide, Fig. 11.6 should be used, where the width, w_B, replaces h_B as the characteristic dimension.

As long as the effective stack height exceeds $l_B/2$ downwind concentrations may be estimated from the conventional Gaussian plume formulae, i.e.,

$$K_{max} = \frac{2}{\pi e} \left(\frac{h_e}{h_B}\right)^{-2} \frac{\sigma_z}{\sigma_y} \cong 0.12 \left(\frac{h_e}{h_B}\right)^{-2}$$

and

$$\frac{x_{max}}{h_B} = \left[\frac{h_e}{\sqrt{2}\ \sigma_z\,(h_B)} \right]^{1/m} \qquad (11.3)$$

where $\sigma_z \sim x^m$.

Fig.11.7 depicts the building downwash influence on maximum concentrations downwind of a stack release. The aerodynamic downwash curve represents an upper bound on the majority of measurements available for a wide range of shapes, orientations, and atmospheric stabilities.

As one might expect, aerodynamic downwash also moves the location of maximum concentration closer to the stack as shown in Fig. 11.8. The data on which this figure is based show a somewhat wider spread than those of the previous figure; however, in this case the curves Eqs. 11.3 provide a lower bound to observations. As noted by Pasquill (1974), pp. 273 ff, the formulae Eq. 11.3 are somewhat stability-dependent and estimate concentrations averaged over at least tens of minutes.

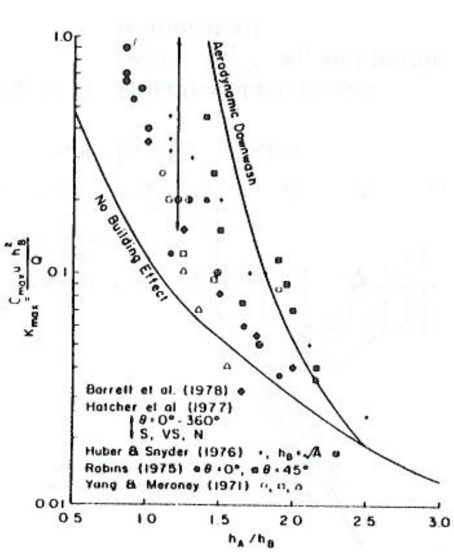


Fig.11.7 Maximum downwind concentrations resulting from aerodynamic downwash (Case $l_B = h_B$)

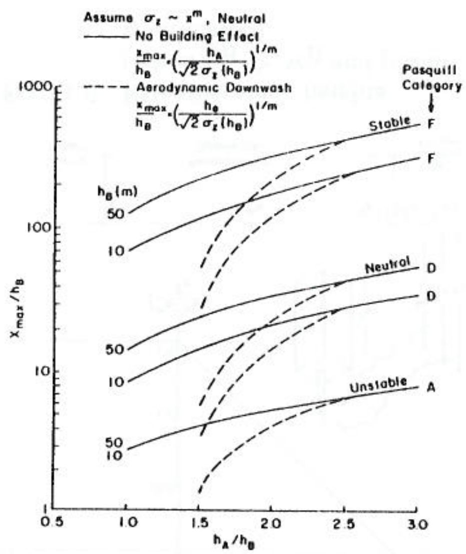


Fig.11.8 Minimum downwind distance to maximum concentrations resulting from aerodynamic downwash (Case $l_B = h_B$; $10 < h_B < 50$ m)

11.2.2 Dispersion Enhancement Models

If one desires to estimate the ground-level centerline variation of concentration downwind of the cavity region in the presence of aerodynamic downwash, or to even estimate cavity entrainment, one has available a bewildering array of formulae. However, if all that is desired is an estimate of average concentration downwind of a source located at or near the building surface, Barry (1964) concluded that most estimates reduced to Eq. 11.1 either in the form:

$$K = C, \quad \text{a constant} \tag{11.4}$$

where one inserts $L^2 = A$ and $u = u(h_B)$ into Eq. 11.1 or

$$K = B_1 \left(\frac{S}{\sqrt{A}}\right)^{-2} \tag{11.5}$$

where $L^2 = A$, $u = u_s$, and S is taut-string distance from source. Constants proposed by various researchers are summarized in Table 11.1.

TABLE 11.1: Recommended dilution coefficients in K equations*

$$K = C_1 \text{ for } \frac{x}{\sqrt{A}} < 3, \quad u = u_{h_B}, \quad \frac{x}{h_B} \sim 3$$

$$K' = B_1 \left(\frac{S}{\sqrt{A}}\right)^{-2} \text{ for } \frac{S}{\sqrt{A}} < 10, \quad u = u_s$$

Investigator	C_1	B_1
Cave and Phillips	0.67	—
Gifford (1960)	0.5 - 2.0	—
Scorer and Bartlett (1962)	—	10
Halitsky (1963a)	2.0 - 5.0	10 - 20
Halitsky (1963b)	—	8 - 8.3
Jensen & Frank (1963)	0.5	—
Briggs (1975)	1.5 - 3.0	4
Wilson (1976)	—	9 - 10

* Extracted in part from Barry (1964), where S is "taut string" distance from source.

Formulae proposed to estimate longitudinal variation of concentration in such situations generally rely on modifications of the values for plume standard deviation, σ_y and σ_z. Gifford (1960) proposed an enhanced dispersion model based on additional dilution of effluent proportional to building cross-sectional area, A, i.e., a concentration coefficient

$$K_o = \frac{A}{\pi \sigma_y \sigma_z + cA} \tag{11.6}$$

where $c = 0.5$ to 2.0. Halitsky (1975), Yansky et al. (1966) and Gifford (1968) also proposed dilution models which retained a Gaussian distribution at the lee end of the cavity. Huber and Snyder (1976) recommended a model for enhanced dispersion based on the decay of turbulent-intensity excess in the building wake and on characteristic building length scales. Huber (1977) also suggested a wake model based on Gifford's meandering plume model. Measurements made downwind of typical building complexes do not seem to justify any degree of complexity (Hatcher and Meroney, 1977). Indeed, Gifford noted that the Gaussian initial volume leads to the simplest justifiable formulation and it is conservative.

An alternative simple approach is that provided by a virtual source displaced by a distance x_s upwind from, and a distance z_s above the actual release location. Extensive measurements provided by Robins (1975) permit the construction of Table 11.2. Concentrations calculated by means of the Gaussian plume model for the various virtual source locations permit one to estimate upper or lower bounds on the surface concentration.

TABLE 11.2: Virtual source locations to represent full entrainment conditions

$$\frac{C u h_B^2}{Q} = \frac{1}{2\pi\,\sigma_y(x')\,\sigma_z(x')}\left[\exp\left(-\frac{1}{2}\frac{y^2}{\sigma_y(x')^2}\right)\right]\cdot$$

$$\left[\exp\left(-\frac{1}{2}\frac{(z-z_s)^2}{\sigma_z(x')^2}\right) + \exp\left(-\frac{1}{2}\frac{(z+z_s)^2}{\sigma_z(x')^2}\right)\right]$$

where $x' = \frac{x - x_s}{h_B}$; $\frac{x}{h_B} > 0.5$

Case	Upper Bound x_s/h_B	Upper Bound z_s/h_B	Lower Bound x_s/h_B	Lower Bound z_s/h_B
Porous Cube	−4.0	0.0	−10.0	0.0
Low Level Point Source, $z/h_B = .13$	0.5	0.0	− 5.0	0.0
High Level Point Source, $z/h_B = .88$	−0.5	0.55	− 1.0	0.8
High Level Line Source, $z/h_B = .88$	−0.5	0.55	− 1.0	0.8
Roof Top Flush Vent, $\theta = 45^o$	0.0	0.0	0.0	0.4
Roof Top Flush Vent, $\theta = 0^o$	0.0	0.55	0.0	0.8

* Data taken from Robins (1975).

A method suitable to interpolate between the cases of aerodynamic downwash and full cavity entrainment situations has been developed by the author based on ideas proposed by Wilson (1976). First one calculates the K_o versus $x/\sqrt{A}$ distribution based on Eq. 11.6; then one prepares the extremum-ratio as follows:

$$\frac{K_{2.5}}{K_o} = \exp\left(-\frac{1}{2}\left(\frac{6.25}{\sigma_z{}^2/A + 1/\pi}\right)\right) \quad ; \qquad (11.7)$$

where $K_{2.5}$ equals K for $h_e/h_B = 2.5$.
Finally one calculates the desired concentration coefficient for the actual effective stack height as

$$K_e = K_{2.5}\left[\frac{K_{2.5}}{K_o}\right]^{\left(\left(\frac{h_e/h_B}{2.5}\right)^2 - 1\right)} \qquad (11.8)$$

The resulting curves shown in Fig. 11.9 agree with selected experimental dat and display the appropriate asymptotic behavior as h_e/h_B varies from 0 to 2.5

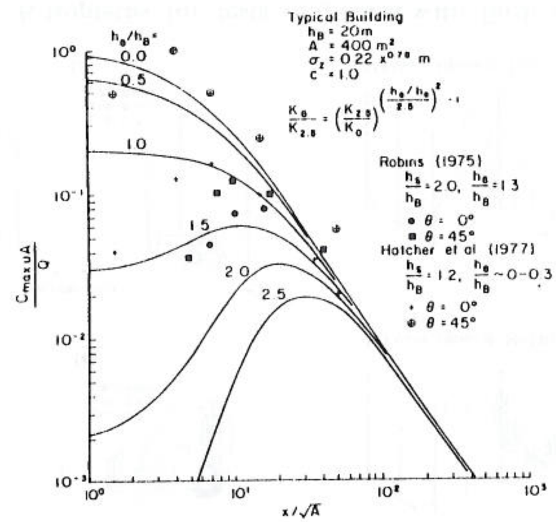


Fig.11.9 Centerline ground level concentrations downwind of a typic isolated building ($h_B \sim 20$ m)

11.2.3 Building Surface to Building Surface Transport

A designer who must dispose of an undesirable vent gas is often faced wit the task of balancing vent stack height, vent exhaust velocity, and intak location. Often his choices are limited by architectural constraints, buildir codes and even noise-control legislation. An increase in vent stack height an vertical exit velocity are usually expected to reduce effluent concentration For most applications the vent gas plume may be considered in a transitiona rise state at all locations over a building roof. The terminal rise may be estima ed from Eq. 11.2; note that this relation conservatively suggests no increas in effective stack height until w_o/u exceeds some critical value. Wilson (197 and Meroney and Yang (1971) found that improvement may occur even fc w_o/u as low as 0.2 as noted in Sketch (a) of Fig. 11.10. Increasing the ver velocity ratios from 0.1 to 1 may reduce receptor concentrations four- t five-fold, because at large vent velocities the plume penetrates the buildir separation streamline and considerable reduces receptor concentrations. Th beneficial aspect of high exit velocities is partly offset by the cost of fan powe Fan power to produce high velocities is proportional to the cube of vent g

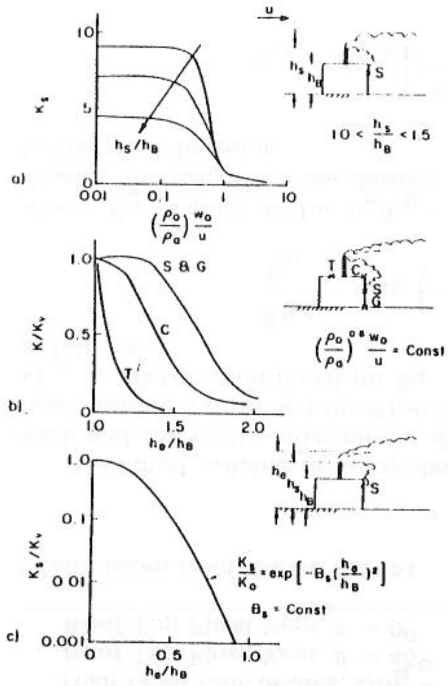


Fig.11.10 Variation of building surface concentrations with short stack characteristics.

velocity; hence, if large exit velocities are required, it may be more attractive to increase vent height itself.

Sketch (b) of Fig. 11.10 is selected from Wilson (1975). He suggests that modest stack height increases together with at least unity velocity ratios will substantially reduce roof top concentrations for h_e/h_B from 1.2 to 1.5. The fact that concentrations on the lee wall of the building do not reduce until h_e/h_B exceeds 1.5 confirms that the streamlines between the cavity envelope and the rooftop separation line return to impinge on the lee surface (see Figs. 11.1 and 11.2). When receptor concentrations are normalized by their flush vent characteristic value K_v, Wilson found that the ratio is directly proportional to the exponential of the square effective stack height as shown in Sketch (c) of Fig. 11.10. Eq. 11.8 where K_o is now interpreted to be equal to K_v, may be used to estimate the relative advantages of two separate design values of effective stack height on concentration. Wilson (1975) concluded that raising a vent has a significant effect only if the vent already is high enough to cause much more dilution than a flush vent.

Since a low velocity vent gas release from a flush vent appears to represent a worst-case condition, it is instructive to see how building geometry, orientation, and source location influence surface concentration coefficient K contours for that case. Halitsky (1961, 1962, 1963a, 1963b) performed dilution measurements about rectangular prismatic shapes, a specific test of the Clinical Center at the National Institute of Health, Bethesda, Maryland, and a specific test on concentrations about the containment vessel of the EBR-II Reactor, Idaho Falls, Idaho. A set of summary surface contours figures may be found in Halitsky (1968). Halitsky suspected his wind tunnel measurements overestimated time mean values in adiabatic conditions by factors up to 10. Munn and Cole (1967) noted that their own prototype measurements were less than those predicted from Halitsky's experience by a factor of 5. Halitsky made his laboratory measurements in a low turbulence uniform velocity field. As noted in chapter 13, Wind Tunnel Modeling of the Atmosphere, replication of the atmospheric surface layer velocity profile, turbulence intensity profile, and

relative length scales are necessary before one can expect kinematic similarity during physical simulation.

Fortunately, Wilson (1976) has recently repeated measurements about rectangular prism shapes in a simulated atmospheric boundary layer. These measurements should be more reliable, and selected figures are arranged for comparison in Figs. 11.11 (a) through (i). Flow visualization made by many investigators suggests that reattachment of separated streamlines on the roof and lee sides of a structure will be a function of building size, length, and approach flow turbulence. Hosker (1979) remarks that most buildings will realize reattachment conditions but locations may vary. Sketches (a), (b), and (c) on the left side of Fig. 11.11 reflect the impressions gained by view-

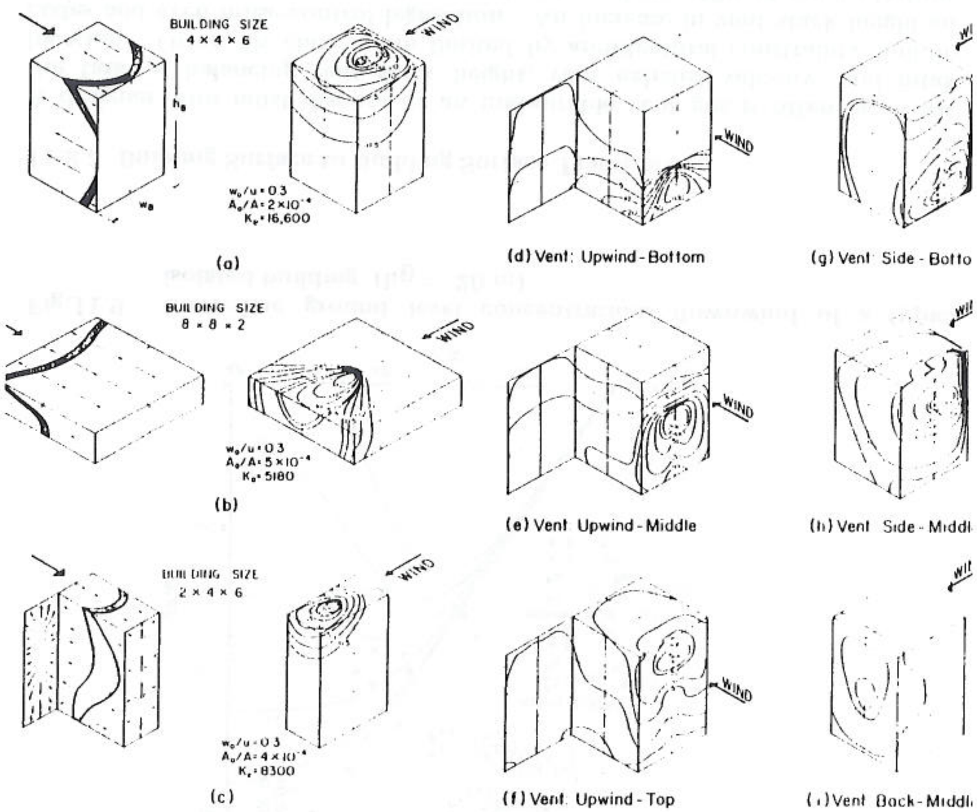


Fig.11.11 K-isopleths for tests of prisms with flush vents. Velocity profile exponent n = 0.23, $h_B/\delta \approx 0.3$, $z_o/h_B \approx 0.05$ or 0.01. For (a) to (c): flush vents are on the rooftop. For (d) to (i): $w_o/u = 0.3$, $A_o/A = 2 \times 10^{-4}$, $K_e = 16{,}600$ (data from Wilson, 1976).

ing colored dye injected near the surface of the buildings. Shaded areas denote regions of intermittent reattachment.

Isopleths joining points of constant concentration factor K are shown in each sketch of Fig. 11.11. Except at points very near the vent, the values of K will be independent of the value of K_e, which is the value of K at the vent exit.

Note that the reattachment locations strongly affect the roof regions contaminated by a roof vent. It is not always true, as one would imply from Halitsky's results, that gases are drawn toward the upwind building edge. For high-rise buildings whose rooftop lies above the most intense regions of atmospheric turbulence and wind shear, reattachment may be absent and rooftop effluents may again travel upwind.

Probably the most accurate means to estimate intake contamination from roof vents is to produce K isopleth curves for each case by physical simulation. In the event such an exercise is not economically justifiable or convenient, dilution factors may be estimated from a number of formulae developed from the wind-tunnel data discussed above. Several authors have suggested the following functional form for estimating dilution:

$$D' = D \frac{w_o A_o}{uA} = B_1 \left(\frac{S}{\sqrt{A}} \right)^2 \tag{11.9}$$

where D is the ratio of vent concentration C_o, to local concentration C, S is the distance from vent to intake found by stretching the shortest possible string between the two points and A_o is the exit area. Halitsky (1962) proposed a constant $B_1 = 0.022$ which underpredicts most dilution by a factor of 2 to 5. Wilson's (1976) value of $B_1 = 0.11$ appears to be an accurate lower bound since 99 % of the recent measurements around two nuclear reactor facilities correlated by Sagendorf et al. (1979) lie above this line.

Based on Halitsky's Clinical Center test ASHRAE (1974) adopted the following formulae:

$$D' = B_2^2 \left(\frac{S}{\sqrt{A}} \right)^2 + 2B_2C \left(\frac{S}{\sqrt{A}} \right) \left(\frac{A_o}{A} \right)^{0.5} + C^2 \frac{A_o}{A} \tag{11.10}$$

where $B_2 = 0.147$ and $C = 4.66$. This formula tends to over-predict dilution near the source. On the other hand, Halitsky's data included measurements above the building surface where concentrations are often higher than at the surface itself. Eqs. 11.9 and 11.10 with different coefficients are displayed together in Fig. 11.12. Halitsky's (1963) curve provides about an order of magnitude factor of safety; whereas Wilson's (1976) curve should provide a lower bound to 99% of all measurements. (Halitsky, 1963; ASHRAE, 1974).

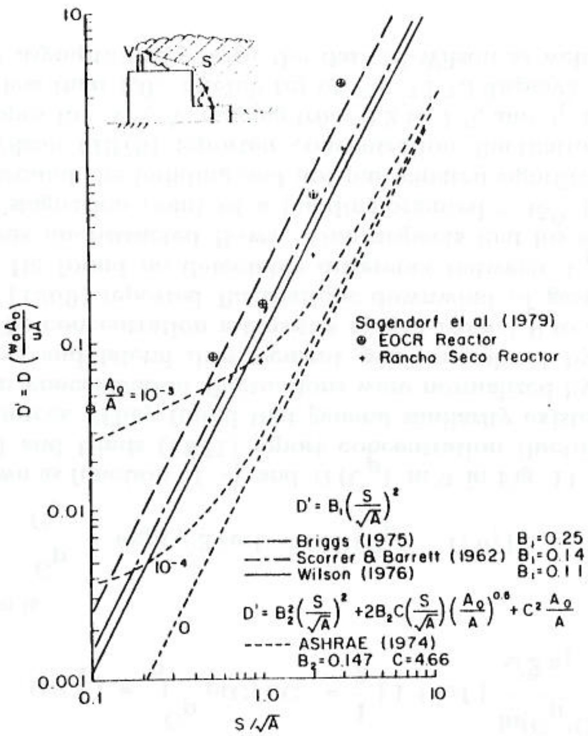


Fig.11.12 Dilution factors to building air intakes from vents.

11.2.4 Peak-to-Mean Concentrations in Building Wakes

When the exhaust gas contains a highly toxic or odorous material, the pea concentrations over a few seconds may be more important to physiologic response than a long time average at the same site (see Fig. 11.13). Ignitio of a flammable gas, for example, is dependent on actual instantaneous fuel/a mixture ratios and not on averages. The instantaneous concentration in building wake is highly variable due to the fluctuations of the separation pr cess, as indicated in Fig. 11.13 a. Hence it is appropriate to suggest a metho to estimate the probability that certain multipliers of the mean concentratio predicted by methods outlined in sections 11.2.2 and 11.2.3 are not exceede

Csanady (1973) summarized the reflections of previous investigators o the concentration fluctuation problem. Measurements reveal that concentra tion fluctuations are log-normally distributed about the mean. Once this i accepted, it is possible to relate mean concentrations to peak concentration via turbulent concentration intensity with confidence, by specifying the pea

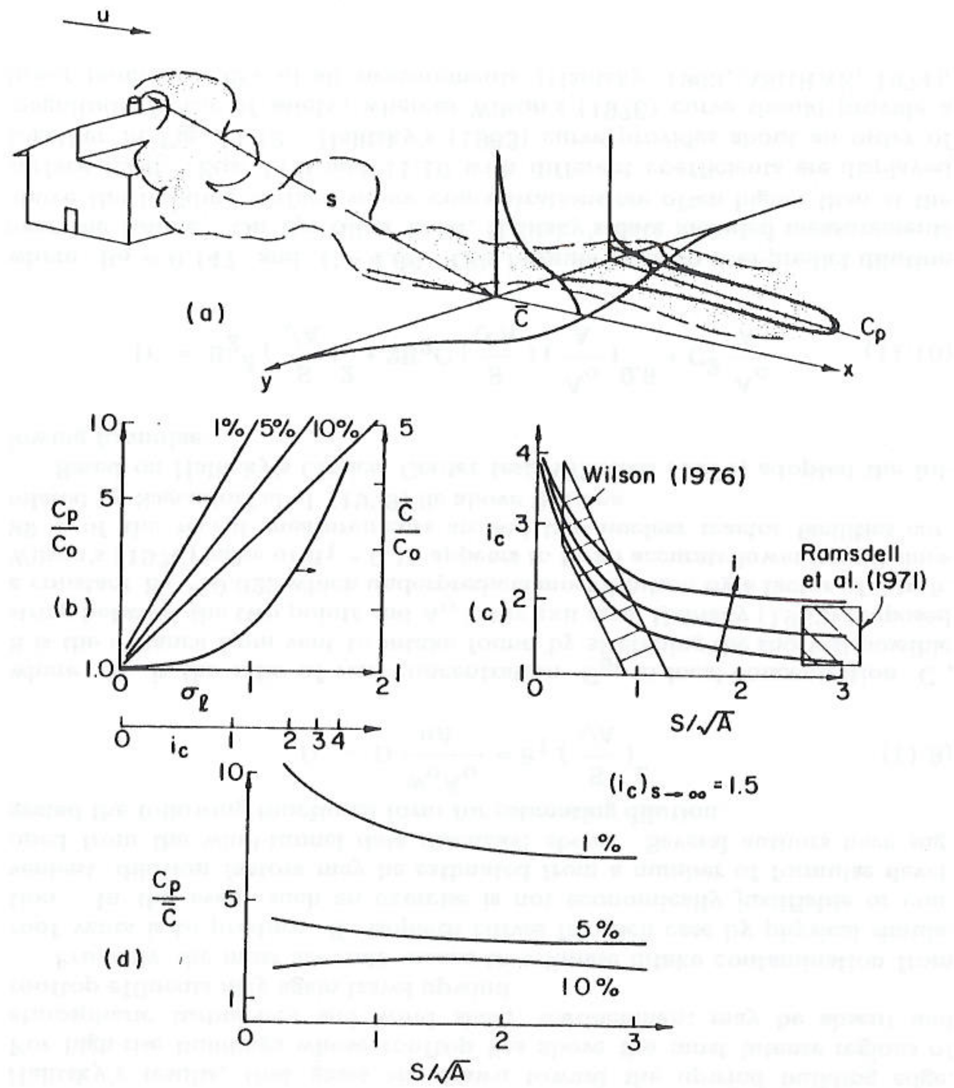


Fig.11.13 Peak-to-mean concentration ratios on building wake centerline

concentration C_p to be that concentration which is exceeded in $1 - \Omega(C_p)$ percent of the cases, where $\Omega(C_p)$ is calculated from the probability density distribution as follows:

The probability density distribution is

$$p(C) = \frac{1}{\sqrt{2\pi}\,\sigma_1 C}\exp\left[-\frac{\left[\ln\left(\frac{C}{C_o}\right)^2\right]}{2\,\sigma_1^2}\right] \tag{11.11}$$

where C_o, the median, is related to $\overline{C}$, the mean, by

$$\frac{C_o}{\overline{C}} = \exp\left(-\frac{\sigma_1^2}{2}\right) , \tag{11.12}$$

and σ_1, the log standard deviation, is related to i_C, the concentration fluctuation intensity, by

$$\sigma_1^2 = \ln\left[i_C^2 + 1\right] . \tag{11.13}$$

The cumulative probability function is related to the probability that a peak concentration, C_p, is not exceeded, i.e.,

$$\Omega(C_p) = \int_0^{C_p} p(C)\,dC = \frac{1}{2}\left[1 + \mathrm{erf}\left[\frac{\ln(C_p/C_o)}{\sqrt{2}\,\sigma_1}\right]\right] \tag{11.14}$$

whose inverse is

$$\frac{C_p}{C_o} = \exp[\sqrt{2}\,(\mathrm{erf}^{-1}(2\Omega(C_p) - 1)\,\sigma_1] . \tag{11.15}$$

which is shown as function of σ_1 and $\Omega(C_p)$ in % in Fig. 11.13 b.

Ramsdell and Hinds (1971) report concentration fluctuations downwind of ground sources. They found that general similarity existed at all distances studied when concentration fluctuations were normalized by centerline mean concentrations and lateral displacement was normalized by lateral standard deviation. The concentration intensities ranged from 1.0 to 2.0 on the centerline. Hinds (1969) reported fluctuations downwind of gases released near a small shed. He found no detectable difference between $C_p/\overline{C}$ ratios in obstructed versus unobstructed flows. One suspects that his releases located at the forward stagnation point of a building oriented ~ 45° to the wind may have swept around the building and not participated significantly in the wake motions. Wilson (1976) reported concentration fluctuations behind model prismatic shapes for $s/\sqrt{A}$ ranging from 0.2 to 1.5, and i_C appeared to range from 3.0 to less than 1.0. Sketch (c) of Fig. 11.13 displays an approximation which agrees asymptotically with the data of Wilson as well as Ramsdell and Hinds, i.e.,

$$(i_C)_{\mathrm{CL}} = (i_C)_{\mathrm{CL}\,\infty} + (4 - (i_C)_{\mathrm{CL}\,\infty}) \exp(-2\frac{S}{\sqrt{A}}) \quad . \qquad (11.16)$$

If one combines this empirical evidence with the implications of a log-normal distribution, a peak-to-mean ratio prediction is prepared such as Sketch (d) of Fig. 11.13. Note that concentrations do not exceed their mean value by more than a factor of 2 more than 10 % of the time at any reasonable distance from the vent. For highly toxic or noxious-odor gases, a factor of safety of 10 should limit a specified concentration from being exceeded more than 1 % of the time in all but the closest locations to the vent.

Most expressions developed here and in chapter 10 are restricted to estimating concentrations for sampling times ranging from ten to thirty minutes. Often regulatory agencies specify limits in terms of sampling times such as 1 minute, 5 minutes, 1 hour, 3 hours, or 24 hours. It is known that average maximum concentrations of gaseous dispersion in the atmosphere tend to decrease with increasing sampling time. Since the motion of air flow in the lower atmosphere is limited in the vertical direction by the presence of the ground, the magnitude of eddy size in the transverse direction may be much greater than that in the vertical direction. Thus, the meandering behavior or gustiness effect because of the large scale of eddy in the atmosphere causes a greater transverse dispersion. Since the larger eddy motion cannot be produced in the wind tunnel, some adjustments must be made for field application.

This phenomenon, often known as the gustiness effect, was first considered by Inoue (Hino, 1968). He reported that a smoke cloud width increases at a rate proportional to the 1/2 power of the observation time. Ogura (1959) developed a mathematical model which suggested a −1/2 power variation of the maximum concentration with time. Hino (1967) performed a large scale study for a time range from ten minutes to five hours. The study which involved releasing tracer materials from high stacks of thermal electric power stations also gives support to the −1/2 power law. Hino also found that atmospheric instability has only small effect on the exponent of the power law. The applicable range of the −1/2 law is greater for unstable than for neutral stratification.

An alternative −1/5 power law was proposed by Nonhebel. Hino (1968) suggested, however, that the applicable time range for this law is less than ten minutes. Other exponents for the peak-to-mean concentration ratio from −0.65 to −0.35 depending on meteorological condition, have been recommended by the ASMC Committee on Air Pollution Control. Hinds (1967) measured the peak-to-mean concentration ratios in a building wake region. Data indicated that the −1/2 law can also be used satisfactorily to predict the dispersion in the wake flow.

More recently, Brun et al. (1973) reviewed all prior experiments for peak-to-mean variations with averaging time. Although they report values of the power law coefficient which vary from 0.12 to 0.86 depending upon stratification and averaging time, they conclude a value of 0.5 is more appropriate when transposing from 0.25 to one hour averaging times. Since times larger than three hours require considerable extrapolation across the spectral gap found in atmospheric turbulence by Van der Hoven, it is doubtful whether one should extrapolate results to 24 hour averages.

11.2.5 Worked Example: SO_2 from a Petroleum Refinery

It is estimated that 0.08 kg/sec^{-1} of sulfur dioxide is being emitted from a petroleum refinery from a 0.5 meter diameter stack 30 meters tall at 4 m sec^{-1}. The stack is located near a structure 15 meters tall by 20 meters wide. At 0500, on an overcast winter morning with a surface wind of 3 m sec^{-1} at 10 meters, what is the maximum surface concentration and its location? What is the surface concentration at 500 meters downwind?

Solution: For overcast night conditions at 3 meters sec^{-1}, D class stability applies (see Table 10.1 chapter 10); other given parameters are:

$h_s = 30$ m	$d_o = 0.5$ m
$h_B = 15$ m	$w_o = 4$ m sec^{-1}
$w_B = 20$ m	$u = 3$ m sec^{-1}
$l_B = 15$ m	$Q = 0.08$ kg/sec^{-1}
$A = h_B \cdot w_B = 300\ m^2$,	$m_o = 64$
$Fr_o = \infty$, which implies that	$(w_o/u)_{critical} = 1.5$.

From Eq. (11.1) $\quad h_A = h_s + 2\,((w_o/u) - 1.5)\,d_o$

$$= 30 + 2(1.33 - 1.5)\,(0.5) = 29.8 \text{ m}.$$

From Fig. 11.5 for $h_A/h_B = 1.99$ one observes that $h_e/h_B = 1.5$. Maximum surface concentration and its location as a result of aerodynamic downwash may be found from Figs. 11.7 and 11.8 respectively, as

$$K_{max} = 0.054, \quad \text{and} \quad \overline{x}_{max}/h_B = 16\ ;$$

hence,

$$C_{max} = K_{max} \cdot (Q/uA) = (0.054)\,(0.08)\,/\,(3)\,(300)$$
$$= 4.8 \times 10^{-6} \text{ kg m}^{-3} \text{ or}$$
$$= 4.8 \times 10^{-6} \times 24 \times 10^{6} / 64$$
$$= 1.80 \text{ ppm} \cdot \text{over 1/3 hour sample time.}$$

The maximum will occur 240 meters downwind of the source.

The concentration at 500 meters may be estimated from Fig.11.9 for $x/\sqrt{A}$ $= 28.9$ and $h_e/h_B = 1.5$ as

$$K = 0.037, \text{ thus}$$
$$C = 3.28 \times 10^{-6} \text{ kg m}^{-3} \text{ or}$$
$$= 1.23 \text{ ppm.}$$

A maximum concentration corrected for a 3 hour sampling time should be

$$C_{3\,hr} = 1.8\left(\frac{1/3}{3}\right)^{1/2} = 0.6 \text{ ppm}.$$

Since a typical regulatory 3 hour ambient concentration standard for SO_2 is 0.5 ppm, this release configuration is at best marginally acceptable under the stated meteorological conditions.

11.3 DIFFUSION NEAR A COLLECTION OF BUILDINGS

When a large collection of buildings perturbs the plume emitted from a site located among them, it becomes difficult to generalize dispersion behavior. If accurate quantitative information is desired, the only recourse is actual in-situ measurements or physical simulation in large atmospheric-boundary-layer wind tunnels. A number of laboratory/field comparisons now exist which give considerable credibility to physical simulation of dispersion in such situations. In a number of cases actual field measurements were made to validate the model procedure, in other situations correct simulation is inferred by the absence of the downwash problems the study was performed to avoid or alleviate. A number of these cases are included among the list of references and are indicated by an asterisk. Review articles of interest include discussions by Wise (1971), McCormack (1971), and Cermak (1974, 1976).

11.3.1 Isolated Building Complex

Groups of buildings associated with fossil or nuclear power stations or certain industrial complexes sometimes stand alone in otherwise rural areas. Halitsky (1975) suggested a variation on the isolated building approach discussed in section 11.2.2 to adjust dispersion for the influence of a group of buildings. Halitsky proposes to use the standard Gaussian plume model but modify σ_y and σ_z. One stipulates that

$$K = \frac{6.25A}{R_y R_z} \exp\left[-3.125\left(\frac{y^2}{R_y^{\,2}} + \frac{z^2}{R_z^{\,2}}\right)\right] \tag{11.17}$$

where $R_y(x) = R_y(o) + 2.5\ \sigma_y(x)$ = plume boundary half width at distance x

$R_z(x) = R_z(o) + 2.5\ \sigma_z(x)$ = plume boundary height at distance x

and $R_y(o)$ = estimate of complex half width

$R_z(o)$ = estimate of complex average height above ground

σ_y, σ_z = standard deviations from conventional charts such as Figs. 10.6 and 10.7

$A = R_y(o)R_z(o)$.

Halitsky (1975) found these expressions agreed with field and laboratory measurements downwind of the EBR-II Reactor, Idaho Falls. Hatcher et al. (1977) found reasonable agreement with data from a simulation of the EOCR Reactor complex also at Idaho Falls; however, values were low in some cases by a factor of 2.

Martin (1965) directly compared average field concentrations within 200 m of sources at the Ford Nuclear Reactor site of the University of Michigan against wind tunnel measurements and the predictions of Sutton's equation (see section 10.2.1). Over a wide range of orientations and atmospberic stratification the field and laboratory values were never more than a factor of 3 apart; yet the analytical expression often underpredicted local concentrations by one to five orders of magnitude!

Most recently, Allwine et al. (1978) and Start et al. (1977) report joint laboratory and field measurements of concentrations about the Rancho Seco nuclear power station, California. Figs. 11.14 (a) and (b) display the 1:500 scale model results for the influence of large (130 m tall) cooling towers on a ground release near the containment vessel. The towers tend to trap gas within the complex and spread the plume laterally when they are located downwind.

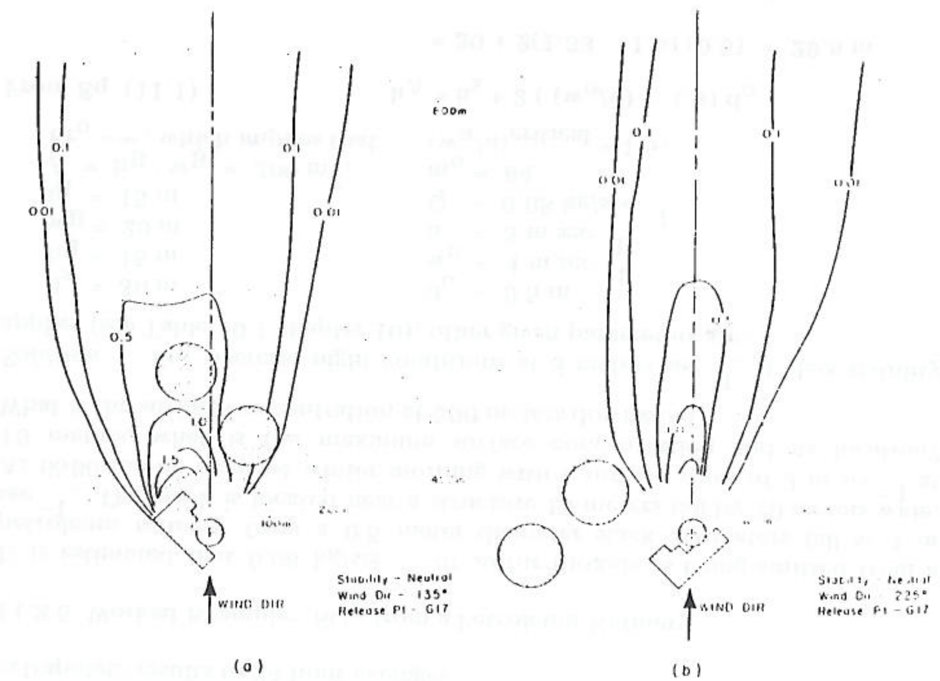


Fig.11.14 Concentration distributions downwind of the Model Rancho Seco nuclear power station building complex.

Field concentrations of SF-6 tracer were gathered over sampling times of one hour during which wind speed and direction varied widely. To compare the hour average field results and 10 minute equivalent laboratory measurements, the wind tunnel data were weighted by orientation, wind speed, and stratification variations to reproduce equivalent one hour sampling averages. Such a weighting procedure reduces field-to-model variation significantly and has essentially validated physical modelling as a methodology.

11.3.2 Influence of Downwind and Upwind Buildings or Topography on Turbulent Diffusion

In some cases a gaseous plume does not interact with buildings or topography at the source but is subsequently perturbed in a downwind portion of its trajectory. The erection of tall buildings often requires estimating whether air pollution being emitted from chimneys in the vicinity can be blown into the building. Fig.11.15 shows plumes impinging in different ways on the face of a rectangular prism. If the plume is on the stagnation streamline, Britter et al. (1976) conclude that when the building is further than ten building widths from the source, concentrations at the building surface are approximately equal to the concentrations which would be found at the same location in the absence of the building. If a source is within ten widths of a tall block building and off the stagnation line, then the plume is generally convected round one side of the building. When a plume stagnates or splits around a building, high ground level concentrations may result from gases transported down the forward face.

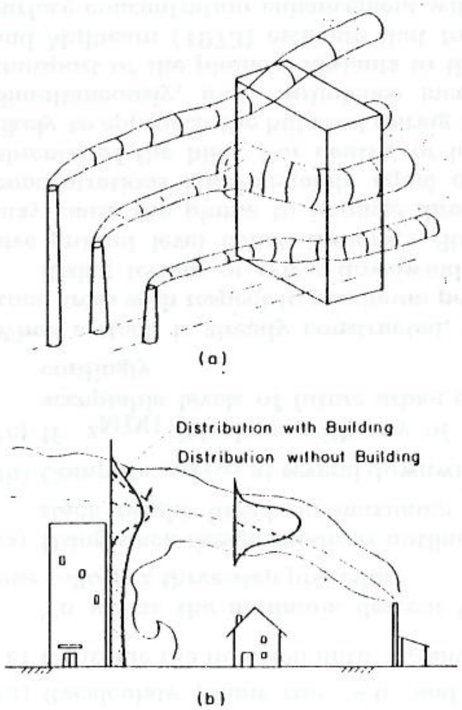


Fig.11.15 Plume impingement perturbations on plume behavior

Lucas (1972) and Wilson and Netterville (1976) have proposed similar methods to estimate minimum descent heights of maximum allowable concentrations based on Gaussian plume dispersion theory. Wilson's method requires the calculation of the minimum descent height, z_{MDH}, of the maximum allowable concentration isopleth C_{ma}, for a range of wind speed and stratification conditions at each downwind distance as indicated in Fig. 11.16 (b) and (c). A mildly unconservative but somewhat simpler technique is to determine the height z_T, at which the furthest extremum of C_{ma} passes over the x location in

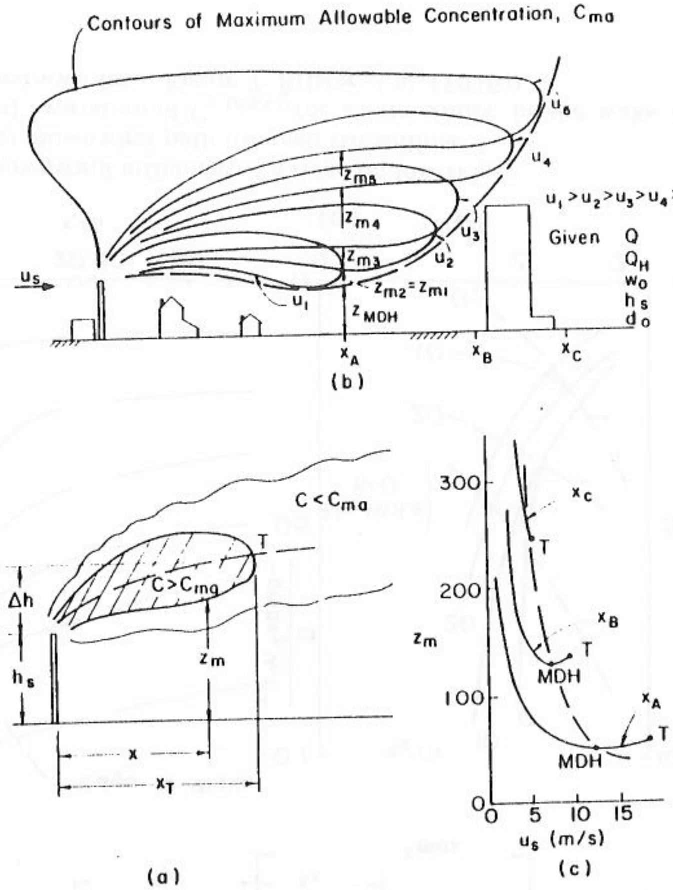


Fig.11.16 Maximum allowable building heights downwind of a short stac[k in]

question; thus (Fig.11.16 (a)):

$$z_{MDH} \sim z_T = h_s + \Delta h \qquad (11.18$$

and the critical velocity, u_T, is

$$u_T = \frac{Q}{2\pi C_A \sigma_y \sigma_z}\left(1 + \exp\left(-2\frac{z_T^2}{\sigma_z^2}\right)\right). \qquad (11.19$$

This equation can be solved at any fixed x location using the followin[g] simple iterative scheme,

(a) Select an initial estimate for u_T.

(b) Compute the plume rise Δh for use in Eq. 11.18 by a method selected from chapter 10.4.
(c) Compute a new value for u_T using Eq. 11.19.
(d) Recalculate plume rise Δh and z_T with the refined estimate of u_T.
(e) Continue the iteration until u_T and z_T no longer change.

To utilize the minimum descent height information during stack design, one follows a three-step procedure:

(a) Using stack design methods outlined in chapter 10, determine the required stack height based on maximum allowable ground level concentrations.
(b) Compute z_{MDH} at several downwind distances to determine its locus.
(c) If z_{MDH} interferes with any of the existing buildings, or is too low for acceptable levels of future urban development, adjust the stack height accordingly.

When a stack is already constructed, the same methodology may be used to zone areas with respect to maximum permissible building height.

Rising terrain or ridges downwind of a stack plume may result in excessive ground level concentrations. Stable stratification or a raised inversion may cause the plume to impinge directly against a hill. In this case, surface concentrations approximately equal centerline plume concentrations in the absence of the hill. For neutral or lapse situations, the plume streamline is likely to approach the hill crest during flow convergence as shown in Fig.11.17. Simultaneously, local turbulence increases which accelerates the turbulent transport of the plume pollutants to the ground (Meroney et al. (1978)). Hunt and Mulhearn (1973) estimate that for a line source upwind of a ridge, the surface concentration enhancement will behave as shown in Fig. 11.17 (b), or

$$\lambda = \frac{C_{g\,max_1}(h)}{C_{g\,max_1}(h=0)} \approx \frac{1}{1 - \dfrac{h^2}{x_p^2 + h_e^2}} \qquad (11.20)$$

Terrain or buildings upwind of a stack may produce significant loss in effective stack height for separation distances x_s/h exceeding 20. Barrett et al. (1978) examined the increase in surface concentrations for plumes released at different downwind distances from a prism set at 45° to the wind. A cube at this orientation is expected to produce maximum centerline downwash as displayed by Fig. 11.2. For small separation distances, x, and short aerodynamic stack heights, h_A, surface concentrations are increased up to one order of magnitude. Even at 30 building heights downwind, there may be a 20% loss in effective stack height for neutrally buoyant plumes as shown in Fig.11.18.

Britter et al. (1976) report a similar plume behavior downwind of ridges.

Streamlines downstream of the crest of a shallow ridge dip toward the surface (Fig. 11.17 (a)). Ground concentrations of a line source released downwind of a hill crest will increase depending upon their relative source height and source-to-crest separation as indicated in Fig.11.17 (b).

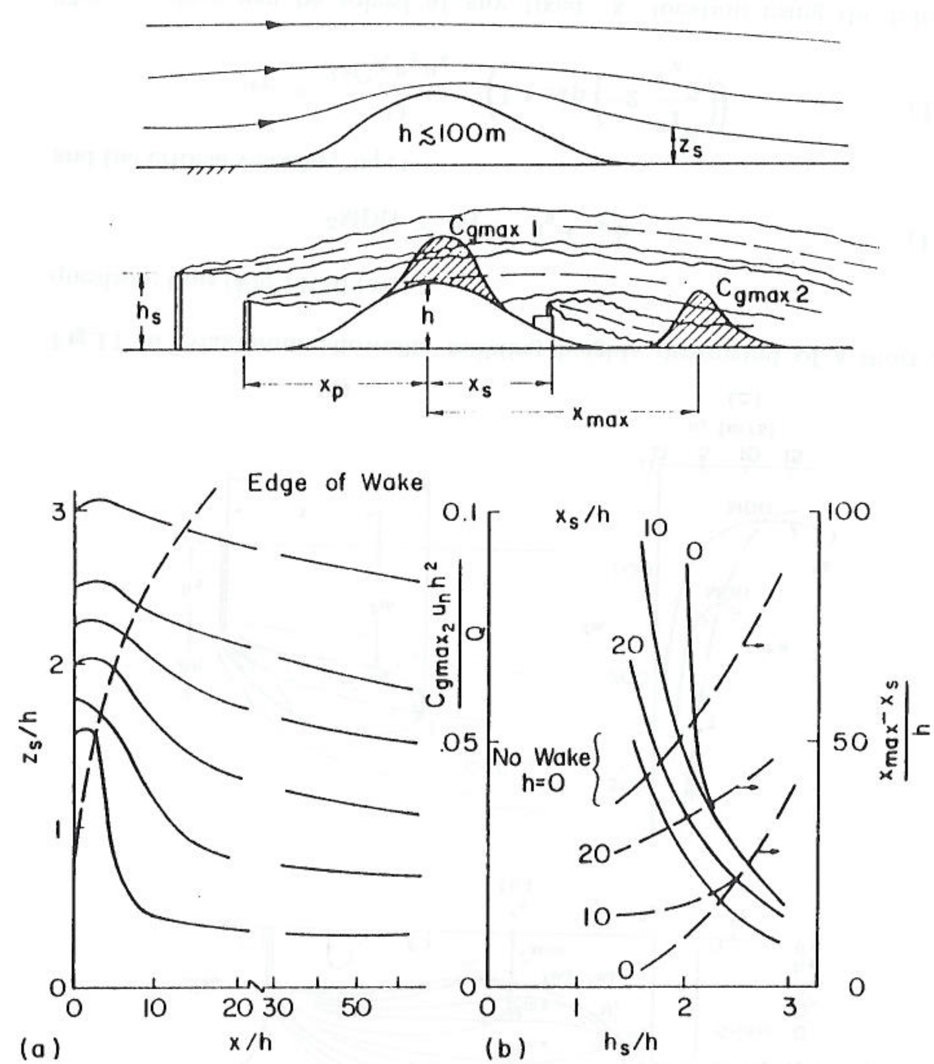
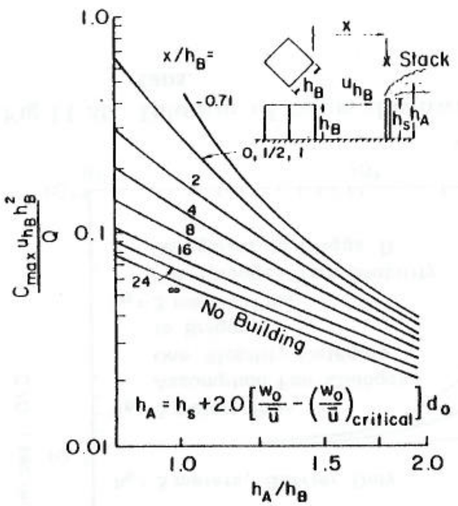


Fig.11.17 Downwind influence of a ridge on low ridges
(a) downwind path of mean streamlines
(b) variation of $C_{g\,max_2}$ for a line source in the wake of a ridge (redrawn from Figure 7, Britter et al. (1976)).



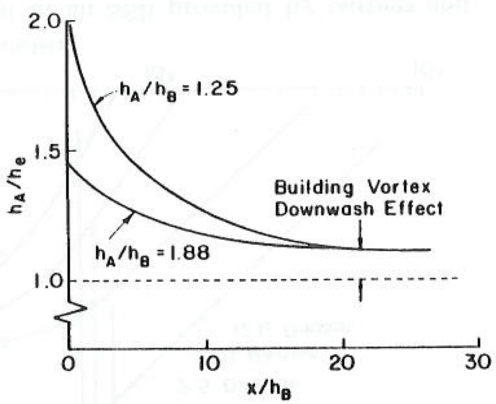


Fig.11.18 (a): Effect of upwind building distance on maximum ground concentration for varying chimney heights (Barret et al. (1978)). (b) Effect of upwind building distance on effective stack height.

11.3.3 Windbreak or Shelter Influence on Dispersion

Vegetative windbreaks or artificial sheltering fences can be constructed deliberately to accelerate dilution. Sewage treatment plants, in particular,often generate noxious odors above settling ponds or sludge storage basins. At night, when wind speeds are low and ground based radiation inversions depress vertical mixing, concentrated odorants may drift into residential areas. A shelterbelt or fence combined with rotating fans used by the fruit-growing industry to avoid frost conditions may dilute odorants below nuisance levels.

Shelterbelt aerodynamics is to a large extent an "ad hoc" science; hence, most design information has rather large error bounds. One should recognize these limitations and include a healthy amount of design conservation where possible. An extensive review on the influence of shelterbelts has been prepared by van Eimern (1964) for the World Meteorological Organization. Relevant subjects considered include the influence of the air's thermal stratification, effectiveness when the wind blows oblique to the barriers, systems of shelterbelts and wind breaks, wind conditions at barrier ends or at gaps, and the barrier influence on evaporation.

As mentioned above, the critical odor situation often occurs during stable situations. Very little research interest has been displayed in the past on wind-barrier effects when velocity is low and stability is strongly stable. Nonetheless, measurements made by Yang and Meroney (1970) over sharp-edged building models under conditions of Pasquill F-G stability (very stable) show aerodynamic mixing predominates in the building vicinity. The net effect on odors will be to mix them vertically over 1.5 to 2 barrier heights. (1.5 to 2.5 barrier heights represents a rule of thumb consensus for the near-fence cavity height.) The highest turbulence increase will be in the free shear flow region near the top of a barrier. For highly stable flows, an upwind blocking may occur; however, this will probably have small effect, since successive barriers will mix downwind odors. Multiple wind barriers will provide an additional opportunity for odors lofted to less stable elevated regions to disperse. The economic trade-off of one tall barrier versus multiple short barriers must be considered for each situation. Fig.11.19 schematically suggests the implications of designing barrier-fan combinations to dilute odors from a surface source.

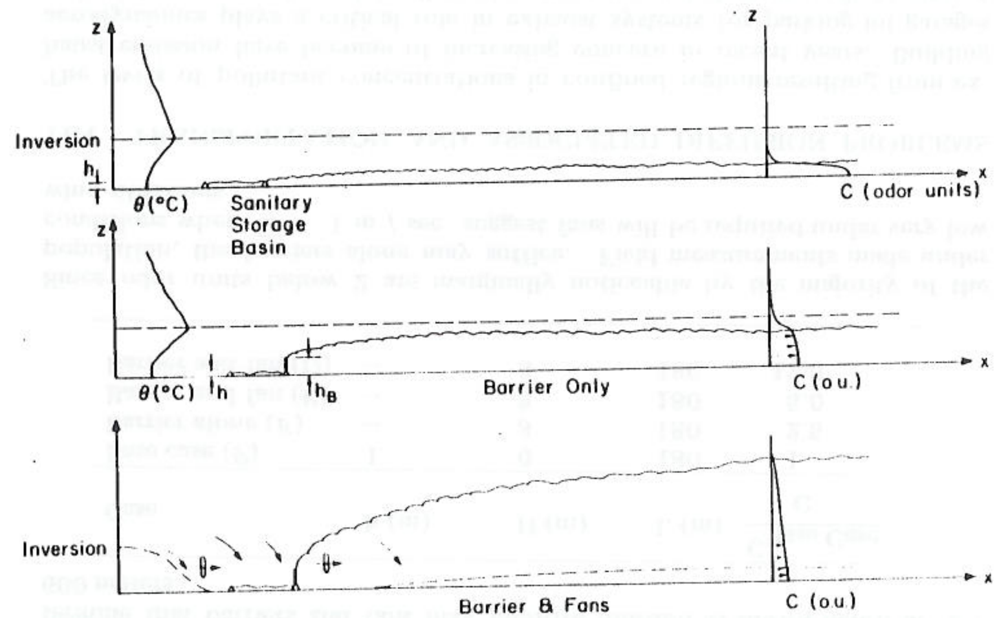


Fig.11.19 Wind barrier and fan-induced dilution of ground level sources

Since vertical transport of scalar products is limited under stable conditions beyond the initial aerodynamic dilution, a modification of Gifford's approach discussed in section 11.2.1 is recommended:

$$K = \frac{C\bar{u}HL}{Q} = \frac{1}{\sqrt{2\pi}\,(\sigma_y^2 + \frac{2}{\pi})^{1/2}} \tag{11.21}$$

where H = barrier height
L = barrier width

$$\sigma_y \cong .04 \frac{x}{\sqrt{HL}} (1 + .0001x)^{-1/2} \text{ (Briggs F stability category)}$$

The addition of wind machines produces a decrease in local stratification by reducing the capping influence of the inversion (see lower sketch, Fig.11.19). If we assume fans decrease stability by one level, one might retain σ_z and calculate standard deviations from

$$\sigma_z = 0.03 \frac{x}{\sqrt{HL}} (1 + .0003x)^{-1}$$

(Briggs E stability category)

$$\sigma_y = 0.06 \frac{x}{\sqrt{HL}} (1 + .0001x)^{-1/2}$$

11.3.4 Worked Example: Odor Dispersal

Consider a sludge settling basin associated with a treatment plant near a metropolitan area. Intermittent release of certain types of sludge causes odorants to

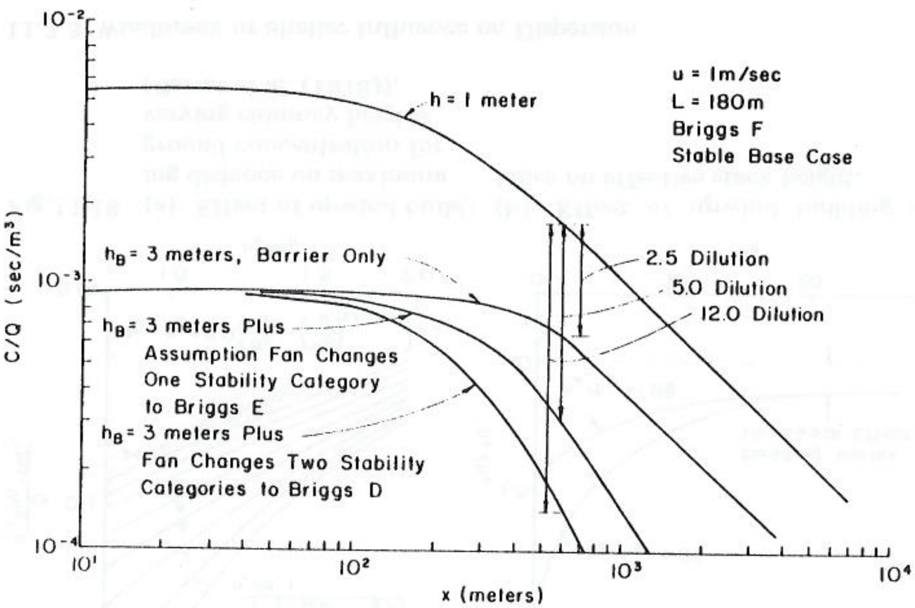


Fig.11.20 Dilution of odors downwind of an SSB provided by barriers and fans.

exceed five odor units at 600 m downwind, which causes numerous complaints. The facility operator desires to alleviate this problem. A typical basin is a square 180 meters on a side surrounded by a berm one meter tall. Critical conditions occur during low wind speed stable conditions; hence

h = 1 meter (initial berm height),
H = 3 meters (proposed barrier height),
L = 180 meters (proposed barrier length),
$\bar{u}$ = 1 m/sec, and
stratification = Briggs F .

Values of C/Q (sec/m^3) as calculated from Eq. 11.21 are plotted versus x (meters) in Fig. 11.20. Thus, given a SSB odor source strength, one can determine that barriers and fans may improve dilution as shown below at x = 600 meters.

Case	h (m)	H (m)	L (m)	$\frac{C_{Base\ Case}}{C}$
Base case (F)	1	0	180	1
Barrier alone (F)	--	3	180	2.5
Barrier and fan (E)	--	3	180	5.0
Barrier and fan (D)	--	3	180	12.0

Since odor units below 2 are marginally noticeable by the majority of the population, the barriers alone may suffice. Field measurements made under conditions when $\bar{u} < 1$ m / sec suggest fans will be required under very low wind situations.

11.4 TRANSPORTATION AND ASSOCIATED DIFFUSION PROBLEMS

The levels of pollutant concentrations in confined regions resulting from exhaust emission have become of increasing concern in recent years. Building aerodynamics plays a critical role in exhaust systems for parking lot garages and highway tunnels and in dispersion near congested areas such as airport terminals. Street canyons and urban freeways also induce their own peculiar circulation patterns. A large selection of numerical programs are now available to predict transport in urban areas (Hanna, 1975) or dispersion near major highway systems (General Electric, 1971; Concaildi et al., 1976). Few programs attempt to adjust for the influence of building-perturbed flow fields other than to modify empirical dilution coefficients in an "ad hoc" manner. A few studies have been performed to determine how the motion of different vehicles modify an exhaust plume (Hall et al., 1973).

A review and bibliography on the aerodynamics and ventilation of vehicle tunnels has been prepared by Pursall and King (1977). Again, as in section 11.3, a majority of the information available depends on specific physical simulation experiments. The discussion here will be limited to specific examples familiar to the author.

11.4.1 Gaseous Pollutants in City Street Canyons

The dispersion of atmospheric contaminants released in automobile exhausts at street level is influenced strongly by local geometry of buildings and trees bounding the street, local topography, and climatological factors of wind speed, wind direction and temperature stratification. Physical modelling of specific city-center areas followed by field measurements to validate methodologies have been performed by several investigators (Kitabayashi et al., 1977 — Tokyo; Plassman et al., 1977 — Cologne; Nishida et al., 1977 — 8 locations in Japan which include a depressed expressway, conventional street, and an elevated highway). Other authors have chosen to study flow over rectangular cavities or generalized building geometries (Hoydysh and Chiu, 1971; Jacko et al., 1972; Ogawa, 1973; Hoydysh and Griffiths, 1974; Wedding et al., 1977).

Hoydysh and Chiu (1971) examined flow in street canyons and pollutant concentrations produced by a street level point source. Their conclusions characterize the flow as either wake-dominated or convection-dominated depending on the crosswind component on the street. By perturbing their city geometry with high rise buildings, they found that the increase in building height near the source and the presence of air spaces enhances ventilation in the street canyon.

Jacko et al. (1971) found that increasing the average height of buildings randomly by a factor of two for the same building density resulted in an increase of ground level pollution downwind of the urban center.

Hoydysh and Griffiths (1974) examined the influence of varying building heights in the vicinity of a line source. They measured concentrations at the "mean roof plane" and found decreases in concentrations on any downwind street for increases in building height. However, as concentration was measured only at an increasing height, the lower concentrations realized could have partially resulted due to the height increase alone and not the greater dilution effect of the geometry.

Wedding et al. (1977) examined flow over a uniform model of 400:1 scale consisting of a complete network of street canyons which were perpendicular to other streets with which they intersected. Measurements were made in the immediate vicinity of a line source at street level, at building surfaces and above the model. Winds were considered perpendicular to street canyons, along the street canyons, and at oblique angles over a variety of variable block configurations.

The configurations and wind orientations considered are shown in Fig.. 11.21. The city blocks were treated as being composed of nine lots, each having the possibility of a building on the lot which could vary in height from 20 to 60 meters. From the results of tracer concentration measurements made in the model city, conclusions can be drawn concerning the effects of wind direction and city building geometry upon the persistence of air pollutants in a city canyon.

(a) *Uniform geometry.* — Winds directed perpendicular to a line of traffic do little to enhance air quality in the street canyon containing the traffic. Generally, air quality was poorest for this wind orientation. Highest pollutant concentrations occurred on the upwind side of the street canyon. This was the result of a standing vortex in the street canyon and poor ventilation of the canyon.

Winds with orientations other than perpendicular to the line of traffic improved air quality in the street containing the traffic. In these cases, spiraling air travelled to the downwind end of the street canyon, dispersing the pollutant. Also clean air can ventilate the street canyon to a greater extent than for the perpendicular winds. Highest pollutant concentrations occurred at the downwind end of the street. These concentrations were generally lower than for the perpendicular winds.

Air quality in the street canyon containing the traffic flow was very good when the wind was oriented parallel to the street. However, localized points

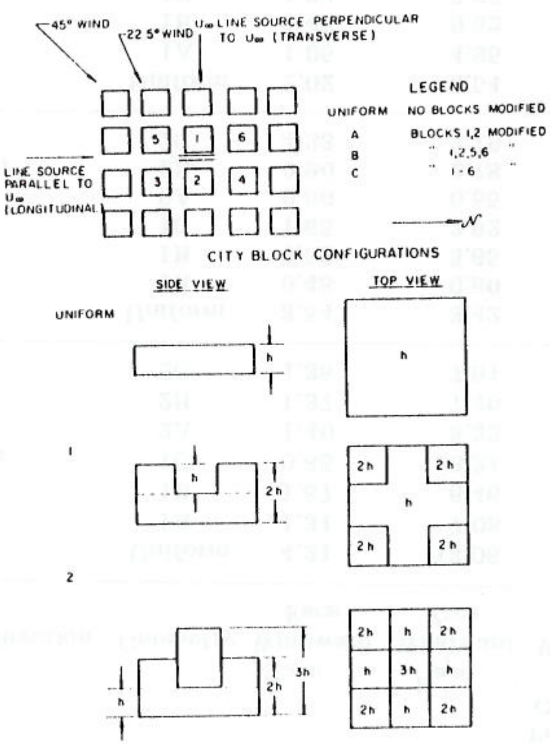


Fig.11.21 Variable city block configurations used by Wedding et al. (1977

of very high pollutant concentration existed at the downwind end of the street canyon for this orientation. This can be a major problem as traffic volume increases.

Overall, the 45^o wind orientation produced the best air quality in the street containing the line of traffic. Highly turbulent clean air can ventilate the street canyon. This orientation is also conducive to transporting pollutants downwind from the street canyon.

Prototype concentrations determined by extending the results obtained from the "traffic-jam" model show that even the "best case", 45^o orientation, produced pollutant levels that approach or exceed U.S. Environmental Protection Agency air quality standards for carbon monoxide. At idle, the average auto emission rate of carbon monoxide is 13 g/min-car, the field- to- model length scale ratio was assumed to be 400:1, and the wind speed at roof level (20 m) is fixed at about 1 m/sec. Assuming an 80-car traffic jam idling in the street canyon, concentrations of CO may be estimated from the concentration coefficient values defined experimentally over the model city, i.e.,

$$C_p = K_{model} \frac{Q_p}{u_p L_p h_p} = 6.12\, K_{model}\ (\text{ppm}) \qquad (11.22)$$

Utilizing Eq. 11.22, average prototype street concentrations of CO have been calculated for different orientations and building geometries from tabulated K values. They are arranged in Table 11.3. The 8 hour ambient air standard for carbon monoxide is 8 parts per million. Average concentrations on the upwind and downwind faces were 25 ppm and 6.1 ppm respectively for the uniform building height geometry with the 45^o wind-line source orientation.

(b) *Geometry modification.* — Significant improvement in air quality resulted as the geometry became more irregular. This result was found regardless of the wind-to-traffic orientation. For cases other than the parallel wind orientation (which exhibited very high local pollutant levels), air quality was as low as 0.34 and 1.36 times the air quality standard for CO (8 ppm for 8 hour exposure). These pollutant levels existed on the canyon walls of the street containing the active traffic.

(c) *The downwind field.* — Air quality was again best for flows directed at an oblique angle to the street with heavy traffic. The wind source orientations which proved most favorable were the 22–1/2^o and 45^o. These orientations produced broad dilute plumes and low street-level pollutant concentrations. Street-level mean concentrations decay most rapidly for the 45^o wind-line source orientation. The decay rate for the mean street-level concentration was

$$K_{ave} \propto x^{-1.5}$$

for streets parallel to the line of traffic

$$K_{ave} \propto x^{-1.25}$$

TABLE 11.3: Mean building face concentrations and equivalent prototype concentrations of carbon monoxide (from Lombardi, 1978).

Mean Wind Direction	Geometry	K_{ave} Windward Face	K_{ave} Windward Face	Prototype Average CO Concentration (ppm) Windward Face	Prototype Average CO Concentration (ppm) Leeward Face
Traffic Jam Perpendicular to u (transverse)	Uniform	4.21	13.08	25.8	80.0
	1A	1.31	7.08	8.0	43.3
	1B	1.87	6.46	11.4	39.5
	1C	0.85	8.21	5.2	50.2
	2A	1.40	8.32	8.6	50.9
	2B	1.37	7.40	8.4	45.3
	2C	1.35	7.91	8.3	48.4
Traffic Jam Parallel to u (longitudinal)	Uniform	3.54	3.42	21.7	20.9
	1A	0.48	0.60	2.9	3.7
	1B	0.52	3.65	3.2	22.3
	1C	1.65	3.92	10.1	24.0
	2A	0.50	0.55	3.1	3.4
	2B	0.90	2.78	5.5	17.0
	2C	4.23	3.19	25.9	19.5
45^o	Uniform	2.02	8.54	12.4	52.3
	1A	1.05	4.95	6.4	30.3
	1B	1.48	9.52	9.1	58.3
	1C	1.94	7.68	11.9	47.0
	2A	0.90	3.60	5.5	22.0
	2B	3.02	4.81	18.4	29.4
	2C	1.36	6.45	8.3	39.5

in the streets perpendicular to the line of traffic. The mean street-level concentration decayed at the slowest rate for the transverse case. For this orientation, the decay rate was found to be

$$K_{ave} \propto x^{-0.65}\ .$$

Increasing building rugosity in the vicinity of the traffic jam increased the street-level air quality in the downwind field for all wind source orientations. The combination of wind oriented at 45^o to the source and rugged geometry in the vicinity of the source produced the most favorable air quality in the downwind field.

11.4.2 Gaseous Pollutants Exhausting from Parking Lot Garages

Underground or covered parking-lot garages are often concentrated sources of automotive exhaust products. When parking area exhausts are combined with unique architectural projections, set-backs, etc., which introduce significant local flow perturbations, the diffusion from a nearby pollution source may be altered greatly. Thus, concentration isopleths do not in practice often conform to such geometrical shapes as are displayed in Fig. 11.11. In such cases, the data on diffusion and wind pressures for simple shapes may not produce realistic estimates. Again, physical simulation often provides the only rational design methodology (see Chaudhry and Cermak, 1971).

11.5 DISPERSION OF DENSE OR COLD GAS PLUMES

Clouds of high-molecular-weight chemical fumes or cryogenic gases released at or near the ground descend rapidly and spread laterally in a "pancake-like" shape. Very little dilution will occur in comparison with normal emissions,and high ground level concentrations of gases which may be toxic or explosive could result.

If a plume contains liquid water at efflux, which is evaporated subsequently as a result of mixing into the surroundings, the latent heat of evaporation is lost, and a negatively buoyant plume may be created. The net temperature deficit can be estimated based on saturation temperature and efflux temperature (Scorer, 1978). As an example, the case of Bankside and Battersea power stations in London may be cited. The flue gases were wet washed to remove almost all (90 %) the SO_2. Gas washing, while reducing the time-mean concentration of the exhaust gas increased the chance for downdraught, building entrainment, and high local concentrations; thus the plume often reached the ground within as few as 5 chimney heights of the source. Hawkins and Nonhebel (1955) reported an average frequency of one puff at ground level every 2 minutes and found that puffs reached the ground immediately downwind from the source at locations where the time average concentrations were previously negligible. Photographs of this behavior are presented by Scorer (1968).

11.5.1 The Fluid Physics of Dense Plume Behavior

As a result of concern over pollution problems associated with the transportation and storage of liquid natural gas (LNG) and other cryogenic substances, the gas and petroleum industries have sponsored a series of studies on cryogenic spills of LNG and other liquids such as liquid oxygen and liquid ammonia on both land (AGA, 1974a; Meroney et al., 1977) and water (Feldbauer et al., 1972; Burgess et al., 1972; etc.). Measurements of plume dispersion downwind of large and small spills have been incorporated into a variety of prediction models (AGA, 1974a; 1974b; Van Ulden, 1974; Germeles and Drake,

1975; Cox and Roe, 1977). Havens (1977) reviewed the efficacy of seven numerical models cited in the literature to describe vapor cloud formation and dispersion from a catastrophic LNG spill. Following a hypothetical 25,000 cubic meter LNG spill onto water, the models variously predicted maximum downwind drift distances to a 5% concentration level (lower flammability limit) ranging from 1.6 to 80.9 kilometers. The variation in the predictions is significant in assessing credibility of potential hazards, yet this uncertainty may well increase when the perturbations of building or structure aerodynamics is considered.

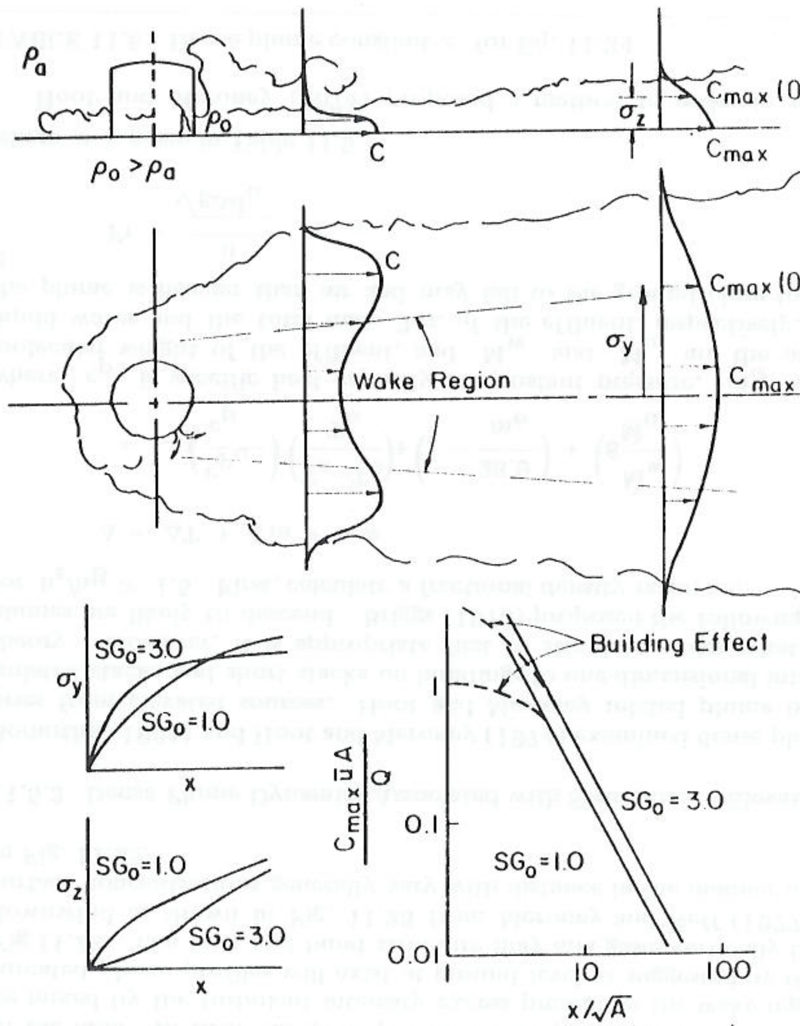


Fig.11.22 Dense plume dispersion ground source release

11.5.2 Dense Plume Dynamics Associated with Structures, Ground Level Release

Density differences were observed by Hoot and Meroney (1974) to have significant effect on the downstream diffusion patterns of a ground source. Lateral spread rate increased and vertical spread rate decreased in the vicinity of a release over that displayed by a neutrally buoyant plume as shown in Fig.11.22. The effect of variation of maximum centerline concentration with distance was primarily multiplicative. Echols (1976) prepared Table 11.4 from this data to provide corrections to conventional Gaussian plume predictions when estimating hazards due to hydrogen sulphide release.

TABLE 11.4: Buoyancy correction factors for various emission configurations

Buoyancy Correction Factor	Emission Configuration	Specific Gravity
1.0	H_2S + natural gas or H_2S released from sour crude	< 1.2
1.3	$H_2S + CO_2$	1.2 to 1.8
1.5	$H_2S + CO_2$ (where emission temperature is less than 30°C below ambient)	> 1.8

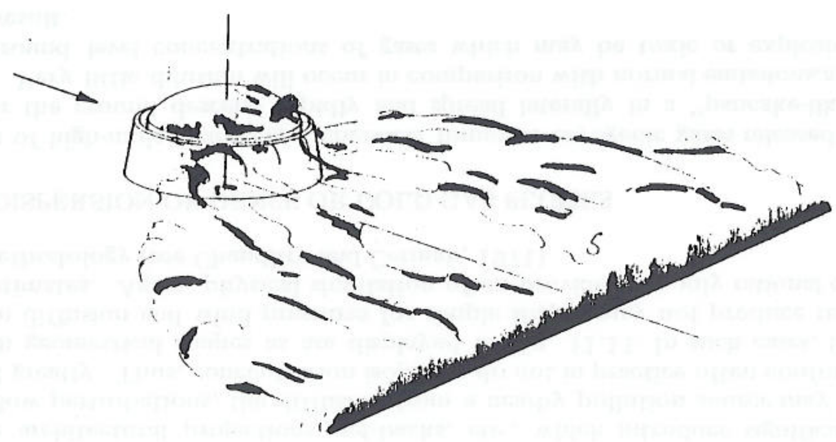


Fig.11.23 Dense gas spreading downwind of a tall dike about a storage tank.

When dense gas clouds result from a breach in a storage tank, the heavy gas may rapidly spread laterally outside the aerodynamic wake region downwind of the tank. In such cases, the portion of the plume outside the wake will not be mixed by the turbulent intensity excess present in the wake region, and bifurcated plume profiles will exist at ground level as suggested by the sketch in Fig.11.22. The tank and bund structure may mix gases vertically immediately downwind as shown in Fig. 11.23 from Meroney and Neff (1977); however, surface concentrations generally vary with distance in the manner of the curves in Fig. 11.22.

11.5.3 Dense Plume Dynamics Associated with Structures — Elevated Releases

Bodurtha (1961) and Hoot and Meroney (1974) examined dense plume trajectories from elevated sources. Hoot and Meroney related plume behavior for isolated stacks and short stacks on buildings to one-dimensional integral plume theory. However, it is appropriate first to stipulate under what conditions plumes are likely to descend. Briggs (1973) proposed the following procedure for $h_s/h_B > 1.5$. First, calculate a fractional density ratio; i.e.,

$$\Delta = \Delta T + \Delta m + \Delta w$$

$$= \left(\frac{c_{p_o}}{c_p}\right)\left(\frac{T_a - T_o}{T_o}\right) + \left(1 - \frac{28.9}{m_o}\right) + \left(8\frac{\dot{M}_w}{\dot{M}_o}\right) \qquad (11.23)$$

where c_p is specific heat capacity at constant pressure, m_o is the mean molecular weight of the effluent, and $\dot{M}_w$ and $\dot{M}_o$ are the mass flux of liquid water and the total mass flux of the effluent, respectively. If $\Delta > 0$, the plume is heavier than air and may fall to the ground close to the source if

$$Fr = \frac{u}{\sqrt{g\Delta d_o}} < c \qquad (11.24)$$

where c is given in Table 11.5.

Hoot and Meroney (1974) proposed a method to estimate surface con-

TABLE 11.5: Dense plume constant c for Eq. 11.24

Condition	Urban Site	Rural Site
Day, u < 3.5 m/sec	0.7	1.0
Day, u > 3.5 m/sec	1.0	2.2
Night, u > 3.5 m/sec	1.5	3.3
Night, u < 3.5 m/sec	2.2	7.7

centrations based on empirical tuning of an analytical plume theory. The components of the analysis requires one to first estimate plume rise, Δh, as

$$\frac{\Delta h}{d_o} = 1.32\,(SG_o)^{2/3}\,Fr^{2/3} R \qquad (11.25)$$

where $SG_o = \rho_o / \rho_a$

$R = w_o/u$

$Fr = u/\sqrt{g \Delta d_o}$, and

downwind distance to maximum plume rise, $\bar{x}$, as

$$\frac{\bar{x}}{d_o} = (SG_o)\,Fr^2 R \, . \qquad (11.26)$$

Touchdown distance, x_{TD}, may be evaluated from

$$\frac{x_{TD} - \bar{x}}{d_o} = 0.56 \left[\frac{\left(\frac{h_s}{d_o} + 2\frac{\Delta h}{d_o}\right)^3 - \left(\frac{\Delta h}{d_o}\right)^3}{R} \right]^{1/2} \cdot Fr \qquad (11.27)$$

(Symbols are defined in Fig. 11.24.)

Note that as $u \to 0$, $Fr \to 0$, $\bar{x} \to 0$, $\Delta h \to 0$ and $x_{TD}/h_s \to 3$ Fr. The constant, 3 , compares well to the value 4.5 proposed by Briggs (1973) based on Bodurtha's visualization experiments.

At touchdown the surface concentrations are of the order

$$\frac{C_{TD} u h_B^2}{Q} \cong 3.1 \left(\frac{2\Delta h + h_s}{h_B}\right)^{-2} . \qquad (11.28)$$

Concentrations decrease from their touchdown values at a negative 0.65 power of distance, x, until the curve intercepts the −1.7 slope behavior of a ground source as shown in Fig.11.24.

If the dense plume touchdown distance, x_{TD}, is less than the building cavity length, then the plume will behave as a ground source perturbed by a building wake as discussed in section 11.2.2.

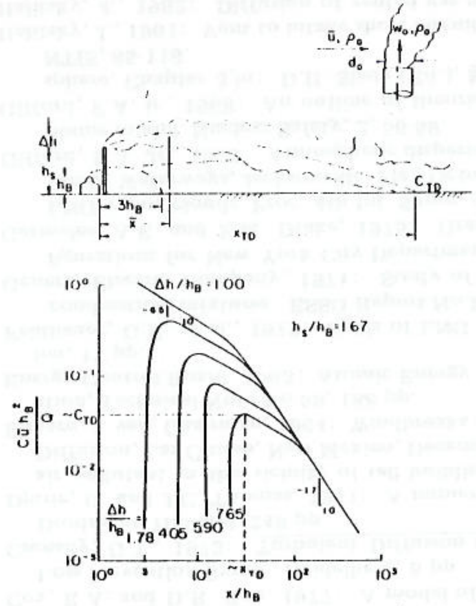


Fig.11.24 Dispersion of dense plumes.

Building cavity length may be estimated from Hosker's (1979) relation

$$\frac{x_{cavity}}{h_B} = \frac{1.75\; W_B / h_B}{1.0 + 0.25\; W_B / h_B} \qquad (11.29)$$

where it is assumed that reattachment occurs on the roof and x_{cavity} is measured from the lee building wall.

REFERENCES

A.S.H.R.A.E., 1974: Handbook and Product Directory, 1974 Applications, Chapter 15, p. 15.9.

Akins, R.E., J.A. Peterka, and J.E. Cermak, 1976: Mean force and moment coefficients for buildings in turbulent boundary layers. J. Ind. Aerodynamics, 2, 195-209.

Allwine, K.J., R.N. Meroney, and J.A. Peterka, 1978: Rancho Seco building wake effects on atmospheric diffusion: simulation in a meteorological wind tunnel. Civil Engineering Department, Colorado State University, Report CER77-78KJA-RNM-JAP25, 175 pp.

American Gas Association, 1974a: LNG safety program, Interim Report on Phase II work. Report on American Gas Association Project IS-3-1, Battelle Columbus Laboratories.

American Gas Association, 1974b: Evaluation of LNG vapor control methods. Report by Arthur D. Little, Inc., Cambridge, Mass., Catalog No. M19875/SC3, 75-469, October.

Barrett, C.F., D.J. Hall, and A.C. Simmonds, 1978: Dispersion from chimneys downwind of cubical buildings — a wind-tunnel study. Paper presented at NATO/CCMS 9th Int.Meeting on Air Pollution Modeling and Its Application, Toronto, Canada, August 28-31, 1978, 8 pp.

Barry, P.J., 1964: Estimation of downwind concentration of airborne effluents discharged in the neighborhood of buildings. Talk presented to Advisory Committee on the Safety of Particle Accelerators of the Atomic Energy Control Board, September 1963, Chalk River, Ontario, 15 pp.

Briggs, G.A., 1973: Diffusion estimation for small emissions. Atmospheric Turbulence and Diffusion Laboratory Report No.79, NOAA, Oak Ridge, Tenn., 61 pp.

Britter, R.E., J.C.R. Hunt, and J.S. Putlock, 1976: Predicting pollution concentrations near buildings and hills. Proc. Conf. Systems and Models in Air and Water Pollution, London, September 22-24, 1976, pp. 7-1 to 7-15, Institute of Measurement and Control, London.

Bodurtha, F.T. Jr., 1961: The behavior of dense stack gases. J. Air Pollution Control Assoc Vol.11, No.9, 431-437.

Brun, J., J. Hugon, and R. Le Quinio, 1973: The effect of exposure duration on the evaluation of coefficients at atmospheric diffusion. Symp. on Physical Behavior of Radioactive Contaminants in the Atmosphere, Vienna, November 12-16, 1973, 15 pp.

Burgess, D.S., J. Biardi, and J.N. Murphy, 1972: Hazards of spillage of LNG into water. Bureau of Mines , MIPR No. Z-70099-9-12395.

Cermak, J.E., 1974: Applications of fluid mechanics to wind engineering — Freeman Scholar lecture, J. Fluids Eng., Vol.97, Ser.1, No.1, 9-38.

Cermak, J.E., 1976: Aerodynamics of buildings. Ann. Rev. Fluid Mechanics, Vol.8, 75-105.

Chaudhry, F. and J.E. Cermak, 1971: Study of wind pressures and air quality around Children's Hospital, National Medical Center, Colorado State University, Civil Engineering Report CER70-71FHC-JEC55, 72 pp.

Clarke, J.H., 1969: Buildings can be well stacked and beautiful too. Industrial Coal Conference, Purdue University, Lafayette, Ind., October 8, 1969, 11 pp.

Concaildi, G.A., A.S. Colnon, and R.F. King, 1976: ANL/HIWAY: An air pollution evaluation model for highways. Argonne National Laboratory Report, ANL-76-XX-37, Argonne, Ill., 141 pp.

Cox, R.A. and D.R. Roe, 1977: A model of the dispersion of dense vapor clouds. 2nd Int. Loss Prevention Symp., Heidelberg, 8 pp.

Csanady, G.T., 1973: Turbulent Diffusion in the Environment, Chapter VIII. D. Reidel, Dordrecht, Holland, 248 pp.

Djuric, D. and J.C. Thomas, 1971: A numerical study of convective transport of a gaseous air pollutant in the vicinity of tall buildings. Symp. on Air Pollution, Turbulence, and Diffusion, Las Cruces, New Mexico, December 7, 1971, 8 pp.

Eimern, J. van, Chairman, 1964: Windbreaks and shelterbelts, World Meteorological Organization, Technical Note No.59, 188 pp.

Energy Control Board, 1963: Atomic Energy of Canada, Ltd., Report AECL-2043, September, 17 pp.

Feldbauer, G.F. et al., 1972: Spills of LNG on water-vaporization and downwind drift of combustible mixtures. ESSO Report No.EE61E-72, November.

General Electric Company, 1971: Study of air pollution aspects of various roadway configurations for New York City Department of Air Resources. NTIS PB 211235, 208 pp.

Germeles, A.E. and E.M. Drake, 1975: Gravity spreading and atmospheric dispersion of LNG vapor clouds. Proc. 4th Int. Symp. on Transport of Hazardous Cargoes by Sea and Inland Waterways, Jacksonville, Fla., October 26-30, 519-539.

Gifford, F.A. Jr., 1960: Atmospheric dispersion calculations using the generalized Gaussian plume model. Nuclear Safety, 2, 56-59.

Gifford, F.A. jr., 1968: An outline of theories of diffusion in the lower layers of the atmosphere, Chapter 3,in: D.H. Slade (Ed.), Meteorology and Atomic Energy, 1968, Avail. NTIS, 65-116.

Halitsky, J., 1961: Vent to intake short circuit. Air Cond. Heat. Vent., p. 81.

Halitsky, J., 1962: Diffusion of vented gas around buildings. J. Air Pollution Control Assoc., 12, 74-80.

Halitsky, J., 1963a: Gas diffusion near buildings. Trans ASHRAE, vol.69, pp. 464 f.

Halitsky, J., J. Golden, P. Halpern, and P. Wu, 1963b: Wind tunnel tests of gas diffusion from a leak in the shell of a nuclear power reactor from a nearby stack. New York University, Department of Meteorology and Oceanography, Geophysical Sciences Laboratory Report No. 63-2, 59 pp.

Halitsky, J., 1968: Gas diffusion near buildings, Chapter 5.5. Meteorology and Atomic Energy - 1968, U.S. Atomic Energy Commission, NTIS, 221-255.

Halitsky, J., 1977: Wake and dispersion models for the EBR II building complex. Atmos. Environ., 11, (7) 577-596.

Hall, D.J., A.C. Simmonds, and J.D. Carrol, 1973: Experiments on the dispersal of exhaust material from diesel vehicles. Warren Springs Laboratory of Trade and Industry Report CR789(AP), U.K., 29 pp.

Hanna, S.R., 1975: Urban diffusion problems, Chapter 6, Lectures on Air Pollution and Environmental Impact Analyses. American Meteorological Society, 209-227.

Hansen, A.C. and J.E. Cermak, 1975: Vortex-containing wakes of surface obstacles. Project THEMIS Technical Report No.29, Civil Engineering Department, Colorado State University, ADA019785, 163 pp.

Hatcher, R.V. and R.N. Meroney, 1977: Dispersion in the wake of a model industrial complex. Joint Conf. on Applications of Air Pollution Meteorology, Proc. Am. Meteorol. Soc., Salt Lake City, Utah, November 29 - December 2, 1977, 343-346.

Hatcher, R.V., R.N. Meroney, J.A. Peterka, and K. Kothari, 1977: Dispersion in the wake of a model industrial complex. U.S. Nuclear Regulatory Commission Report NUREG-0373, 231 pp.

Havens, J., 1977: Predictability of LNG vapor dispersion from catastrophic spills onto water: an assessment. U.S. Coast Guard, Department of Transportation, Report CG-M-09-87, 211 pp.

Hawkins, J.E. and G. Nonhebel, 1955: Chimneys and the dispersal of smoke. J. Inst. Fuel, 28, 530-545.

Hinds, W.T., 1969: Peak-to-mean concentration ratios from ground-level sources in building wakes. Atmos. Environ., 3, 145-156.

Hino, M., 1968: Maximum ground level concentration and sampling time. Atmos. Environ., 2, 149-165.

Hoot, T.G. and R.N. Meroney, 1974, The behavior of negatively buoyant stack gases. 67th Annual Meeting APCA, June 9-13, 1973, Denver, Colorado, Paper No.74-210, 21 pp.

Hosker, R.P. Jr., 1979: Empirical estimation of wake cavity size behind block-type structures. Fourth Symp. on Turbulence, Diffusion, and Air Pollution, Am. Meteorol.Soc., Reno, Nevada, January 15-18, 1979, 603-609.

Hoydysh, W.G. and H.H. Chiu, 1971: An experimental and theoretical investigation of the dispersion of carbon monoxide in the urban complex. AIAA Paper No.71-523.

Hoydysh, W.G. and R.A. Griffiths, 1974: A scale model study of the dispersion of pollutant in street canyons. Paper No. 74-157, 67th Annual Meeting of APCA, Denver, Colo., June 1974.

Huber, A.H. and W.H. Snyder, 1976: Building wake effects on short stack effluents. Third Symp. on Atmospheric Turbulence, Diffusion and Air Quality, Am. Meteorol. Soc., Raleigh, N.C., October 19-22, 1976, 235-242.

Huber, A.H., 1977: Incorporating building/terrain wake effects on stack effluents. Joint Conf. on Applications of Air Pollution Meteorology, Proc. Am. Meteorol. Soc., Salt Lake City, Utah, November 29 - December 2, 1977, 353-356.

Hunt, J.C.R. and P.J. Mulhearn, 1973: Turbulent dispersion from sources near two-dimensional obstacles. J. Fluid Mech., 61, Part 2, 245-274.

Hunt, J.C.R., C.J. Abell, J.A. Peterka, and H. Woo, 1978: Kinematical studies of the flows around free or surface-mounted obstacles; applying topology to flow visualization. J. Fluid Mech., 86, Part 1, 179-200.

Jacko, R.B., G.M. Palmer, and D.L. Brenchley, 1972: A wind-tunnel study to determine the air pollution dispersion characteristics in an urban center. Paper No. 72-137, 65th Annual Meeting of APCA, Miami Beach, Fla, June 1972.

Kitabayashi, K., K. Suguwara, and S. Isomura, 1977: A wind-tunnel study of automobile exhaust gas diffusion in an urban district. Proc. 4th Int. Clean Air Congress, Tokyo, Japan, May 16-20, 192-195.

Lantz, R.B., 1972: Application of a three-dimensional numerical model to air pollutant calculations. 65th Annual Meeting of APCA, Miami Beach, Fla., June 18-22, 1972, Paper 72-141, 26 pp.

Lavery, T.F., B.A. Egan, and R.M. Iwonchuk, 1974: The numerical simulation of the advection and diffusion of a plume under aerodynamic downwash conditions. Paper 74-215, 67th Annual Meeting of APCA, Denver, Colo, June 1974, 15 pp.

Lombardi, D.J., 1978: Steady state pollutant concentrations in an urban area. M.S. Thesis, Civil Engineering Department, Colorado State University, Fort Collins, 109 pp.

Lucas, D.H., 1972: Choosing chimney heights in the presence of buildings. Proc. Int. Clean Air Conf., Melbourne, Australia, 47-52.

McCormick, R.A., 1971: Air pollution in the locality of buildings. Phil. Trans. Roy. Soc. London, A, 269, 515-526.

Martin, J.E., 1965: The correlation of wind tunnel and field measurements of gas diffusion using Krypton-85 as a tracer. Ph.D. Dissertation, University of Michigan (also Michigan Memorial Phoenix Project Report MMPP 272), 130 pp.

Meroney, R.N. and B.T. Yang, 1971: Wind-tunnel study of gaseous mixing due to various stack heights and injection rates above an isolated structure. U.S. Atomic Energy Commission Report No. C00-2053-6, Colorado State University Report No. CER71-72-RNM-BTY16, 42 pp.

Meroney, R.N., J.E. Cermak, and D.E. Neff, 1976: Dispersion of vapor from LNG spills simulation in a meteorological wind tunnel. Proc. 3rd AMS Symp. on Atmospheric Turbulence, Diffusion, and Air Quality, October 19-22, 1976, Raleigh, N.C.,243-246.

Meroney, R.N., and D.E. Neff, 1977: Behavior of negatively buoyant gas plumes from an LNG spill. 6th Australasian Hydraulics and Fluid Mechanics Conf., University of Adelaide, Australia, 4 pp., December 5-9, 1977, Colorado State University, Fort Collins, Colo., Report No. CEP77-78RNM-DEN1.

Meroney, R.N., V.A. Sandborn, R.J.B. Bouwmeester, H.C. Chien, and M. Rider, 1978: Sites for wind power installations: physical modelling of the influence of hills, ridges and complex terrain on wind speed and turbulence. Department of Energy Report RLO/2438-77/3, or Colorado State University Report No. CER77-78RNM-VAS50, 175 pp.

Munn, R.E. and A.F.W. Cole, 1967: Turbulence and Diffusion in the Wake of a Building. Atmos. Environ., 1, 33-43.

Nishida, K., T. Yamamoto, Y. Itokura, and K. Mizuta, 1977: Wind-tunnel experiments on atmospheric diffusion of automobile exhaust gases due to highway traffic. Proc. 4th Int. Clean Air Congress, Tokyo, Japan, May 16-20, 1977, 196-200.

Ogura, Y., 1959: Diffusion from a continuous source in relation to a finite observation interval. Adv. Geophys., 6, 149-159.

Pasquill, F., 1974: Atmospheric Diffusion, Halsted Press, New York, 2nd edn., 429 pp.

Plassman, E., P. Leisen, and H. Sobottka, 1977: Atmospheric dispersion of motor vehicle exhaust gases in urban areas. Proc. 4th Int. Clean Air Congress, Tokyo, Japan, May 16-20, 1977, 238-241.

Pursall, B.R. and A.L. King, 1977: Review and Bibliography: Aerodynamics and Ventilation of Vehicle Tunnels, BHRA Fluid Engineering, Cranfield, England, 237 pp.

Ramsdell, J.V. Jr. and W.T. Hinds, 1971: Concentration fluctuations and peak-to-mean concentration ratios in plumes from a ground-level continuous point source. Atmos. Environ., 5, 483-495.

Robins, A.G. and I.P. Casho, 1977: A wind-tunnel investigation of plume dispersion in the vicinity of a surface mounted cube — I. The flow field. Atmos. Environ., 11, 291-297; II. The concentration field. Atmos. Environ., 11, 299-311. (Also see Robins, 1975: Central Electric Generating Board Report R/M/R220, U.K., 49 pp.)

Sagendorf, J.F., N.R. Ricks, G.E. Start, and C.R. Dickson, 1979: Near building diffusion determined from atmospheric tracer experiments. 4th Symp. on Turbulence, Diffusion, and Air Pollution. Proc. Am. Meteorol. Soc., Reno, Nevada, January 15-18, 1979, 596-602.

Scorer, R.S., 1959: The behavior of chimney plumes. Int. J. Air Pollut., 1, 198-220.

Scorer, R.S., 1968: Air Pollution. Pergamon, New York, 151 pp.

Scorer, R.S., 1978: Environmental Aerodynamics. Halsted Press, New York, 488 pp.

Start, G.E., J.H. Cate, C.R. Dickson, N.R. Ricks, G.R. Ackermann, and J.F. Sagendorf, 1977: Rancho Seco building wake effects on atmospheric diffusion. NOAA Tech. Memo ERL, ARL-69, 185 pp.

Ukeguichi, W., H. Okamoto, and R. Ohba, 1975: The numerical analysis of the diffusion around structures. Proc. Int. Clean Air Conf., Rotarua, New Zealand, 21 pp.

Van Ulden, A.P., 1974: On the spreading of a heavy gas released near the ground, Loss Prevention and Safety Promotion in the Process Industries, Elsevier, Amsterdam, 1974, p. 222 /6 pp.&.

Wedding, J.B., D.J. Lombardi, and J.E. Cermak, 1977: A wind-tunnel study of gaseous pollutants in city street canyons. J. Air Pollution Control Assoc., 27, No.6, 557-566.

Wilson, D.J. and D.D.J. Netterville, 1976: Influence of downwind high-rise buildings on stack design. J. Air Pollution Control Assoc., 26 (10), 976-980.

Wilson, D.J., 1976: Contamination of building air intakes from nearby vents. Dept. Mech. Eng. Report No.1, University of Alberta, Edmonton, Canada, 126 pp.

Wise, A.F.E., 1971: Effects of groups of buildings. Phil. Trans. Roy. Soc. London, A, 269, 469-485.

Yang, B.T. and R.N. Meroney, 1970: Gaseous dispersion into stratified building wakes. Atomic Energy Commission Report No. C00-2053-3, or Colorado State University, Civil Engineering Department, Report CER70-71BTY-RNM8, 103 pp.

Yanskey, G.R., E.H. Markee Jr., and A.P. Richter, 1966: Climatology of the National Reactor Testing Station, Report IDO-12048, U.S. Atomic Energy Commission, Idaho Falls, Idaho, 184 pp.