Chapter 7
Wind-Induced Dispersion of Pollutants in the Urban Environment

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Abstract Predicting air and pollutant flow around buildings in an urban environment is a very complex problem affecting building design and performance. This chapter presents some of the new developments in this field, as far as the assessment of pollutant concentrations is concerned and the evolving design guidelines in this area. Particular emphasis is placed on the results of wind tunnel studies to assess the influence of adjacent buildings and rooftop structures on near-field pollutant dispersion by considering various parameters, such as stack height, exhaust momentum and spacing between buildings. A general discussion of the various ASHRAE models, as well as comparisons with wind tunnel results for a few adjacent building configurations, is presented. Application of ADMS, a Gaussian-based dispersion model, on near-field pollutant dispersion is also discussed. Comparisons for computational fluid dynamics (CFD) results and wind tunnel data for a particular case are made. The limitations of ASHRAE and CFD models to predict realistic dilutions for particular building configurations, besides suggestions to improve them, are discussed. Guidelines regarding appropriate stack and intake locations to avoid plume reingestion are also presented.

Keywords ASHRAE • Building • Dilution • Wind tunnel • CFD

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7.1 Introduction

This chapter focuses on the effects of wind-induced pollutant dispersion from rooftop emissions in the built environment through various experimental and analytical studies, carried out in the last decade. The experimental results mainly originate from wind tunnel measurements, while analytical techniques pertain to ASHRAE and ADMS formulations. Additionally, a brief discussion on the application of computational fluid dynamics (CFD) models is presented. Current standards for building ventilation systems recommend that rooftop stacks from industrial, laboratory or hospital buildings be designed such that their emissions do not contaminate fresh air intakes of the emitting building or nearby buildings. Unfortunately, the state of the art has not been sufficiently advanced to allow building engineers to apply appropriate design criteria to avoid this problem for new construction or to help alleviate it for existing buildings. Several instances of potential health hazards due to pollutant reingestion from isolated buildings, as well as limited studies on adjacent building configurations, are available in the literature (e.g. Schulman and Scire 1991; Wilson et al. 1998). Recently, Hajra et al. (2011) performed a detailed wind tunnel study to assess the effects of upstream buildings on near-field pollutant concentrations and found that the height and across wind dimensions of the upstream building, as well as the spacing between buildings, were critical parameters in altering the plume geometry. More recently, Hajra and Stathopoulos (2012) showed that a taller downstream building prevents pollutants from dispersing, thereby increasing rooftop concentrations on the emitting building.

Besides wind tunnel studies, field measurements of tracer studies were also carried out in the past. For instance, field studies by Wilson and Lamb (1994) have shown that even with high exit velocities and moderately high stacks, pollutant concentrations may be unacceptably high at particular locations. Studies by Stathopoulos et al. (2004) carried out on two of the buildings located at Concordia University, Canada, have also shown that a taller upstream building, with effluents being released from a lower downstream building, may affect the leeward wall of the upstream building, as well as the roof of the emitting building. In general, several factors may account for the occasional poor performance of rooftop stacks. These factors include the location of the stack relative to regions of flow separation and flow reattachment, the presence of rooftop irregularities such as penthouses and high upstream turbulence. Relatively few studies have compared wind tunnel concentration data with field measurements for near-field diffusion cases (i.e. receptors within 50 m of a stack). This is one of the most difficult fluid modelling applications, since the plume characteristics may be sensitive to a number of local factors (building wake effects, the position of the stack relative to rooftop recirculation zones, stack Reynolds number, etc). On the other hand, for far-field applications, plume characteristics are much less sensitive to these factors. Higson et al. (1994) conducted field tracer gas experiments with a stack at varying distances upwind of a small building and found that the maximum concentrations were generally overestimated in the wind tunnel tests, while the minimum concentrations were underestimated. This suggests that the wind tunnel plume was narrower than the field plume due to the absence of large-scale turbulence in the wind tunnel. Several studies at Concordia University have evaluated the accuracy of wind tunnel dispersion measurements (Stathopoulos et al. 1999, 2004) and found generally good agreement between wind tunnel and field data. The wind tunnel concentration values were usually within a factor of 2 of the field values. In general, the accuracy of the wind tunnel generally increases as stack-receptor distance increases.

Various semiempirical models have been developed by ASHRAE for estimating near-field dilution of plumes emitted from rooftop stacks for open fetch situations. The models can be used to assess the minimum stack height to avoid plume reingestion (geometric design method) and Gaussian plume equations to assess plume dilutions on rooftop receptors. These models include ASHRAE (1997, 1999, 2003, 2007, 2011). ASHRAE (1997, 1999) are mainly based on the works of Halitsky (1963), while the 2003 and 2007 versions are based on the efforts of Wilson (1979). The more recent version of ASHRAE 2011 has been developed primarily by Petersen et al. (2004). The accuracy of these models has been evaluated by various researchers, and with the exception of ASHRAE 2011, most of these models were found to be overly conservative for isolated buildings (Stathopoulos et al. 2004; Hajra et al. 2011, 2013). Additionally, these models were found to be incapable of simulating the effects of rooftop structure and adjacent buildings (Stathopoulos et al. 2008; Gupta et al. 2012). However, ASHRAE 2011 predictions were found to be reasonably accurate for an isolated building with low exhaust speeds. Furthermore, the 2011 version also provides guidelines to determine dilutions on the sidewalls of an emitting building, as opposed to previous versions that were only restricted to rooftop dilutions on the source (Hajra et al. 2013). Dispersion models developed by the Environmental Protection Agency (EPA) are mainly suited for far-field pollutant dispersion problems, as they cannot model the turbulence caused by buildings and structures in the near vicinity of the source (Stathopoulos et al. 2008). CFD has been used extensively in the last few decades to model pollutant dispersion in the urban environment (Tominaga and Stathopoulos 2007). Unfortunately, CFD simulations cannot accurately predict the air and pollutant flow characteristics around buildings, making it necessary to carry out additional experimental studies for realistic urban layouts, in order to improve CFD (Blocken et al. 2011).

7.2 ASHRAE Dispersion Models

The various versions of ASHRAE described in this section include 1997, 1999, 2003, 2007 and 2011. The dilution equations in 1997 and 1999 versions are essentially non-Gaussian, while the 2003, 2007 and 2011 versions are semi-Gaussian models. It is worth mentioning that the ASHRAE models use the geometric design method, which is common to all versions, and the equations for estimating dilutions, which are somewhat different for each version.

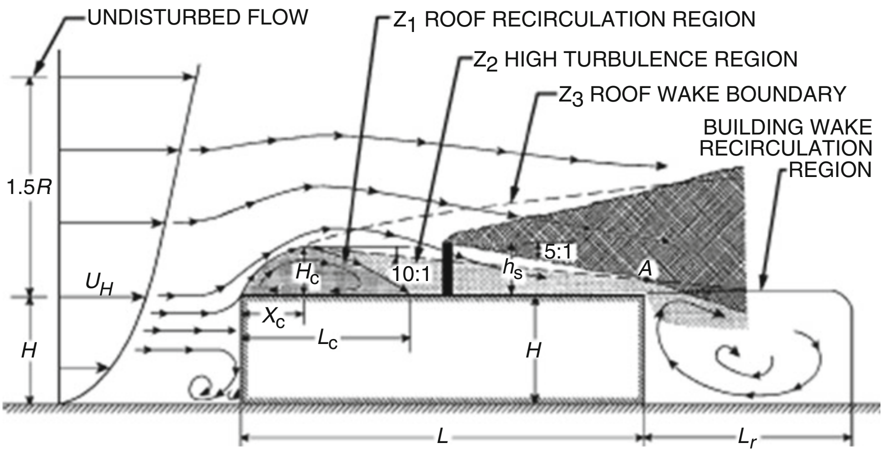

Fig. 7.1 Design procedure for required stack height to avoid contamination (Wilson 1979)

7.2.1 Geometric Design Method

The geometric design method provided in all versions of ASHRAE (1997, 1999, 2003, 2007, 2011) has remained unchanged. This method is used to estimate the minimum stack height to avoid plume entrainment in the flow recirculation zones of a building and its rooftop structures. Dimensions of the recirculation zones are expressed in terms of the building dimensions (Fig. 7.1):

$$L_r = B_s^{0.67} B_L^{0.33} \tag{7.1}$$

where B_s is the smaller of upwind building height or width and B_L is the larger of these dimensions. The dimensions of flow recirculation zones that form on the building and rooftop structures are

$$H_c = 0.22L_r \tag{7.2}$$

$$X_c = 0.5L_r \tag{7.3}$$

$$L_c = 0.9L_r \tag{7.4}$$

where H_c is the maximum height of the roof recirculation zone, X_c is the distance from the leading edge to H_c, L_c is the length of the roof recirculation zone and L_r is the length of the building wake zone.

The design method assumes that the boundary of the high turbulence region is defined by a line with a slope of 10:1 extending from the top of the leading edge separation bubble. The location of the plume relative to the recirculation zones is determined by taking into account plume rise due to exhaust momentum and assuming a conical plume with a slope of 5:1. It should be noted that the geometric design method is applicable for wind directions that are approximately normal to the windward wall of the building, which is the critical case for flat-roof buildings

(Saathoff et al. 2009). On the other hand, for oblique winds, building-generated turbulence is normally not significant in the central part of the roof (where stacks are usually located). For such winds, the building-generated turbulence is confined to the leading edges of the roof where the familiar delta-wing vortices are formed.

7.2.2 Gaussian Plume Equations

Gaussian plume equations have remained unchanged for 1997 and 1999 versions, while changes have been suggested to the 2003, 2007 and 2011 versions, as will be discussed further herein.

7.2.2.1 ASHRAE 1997/1999

Two different sets of equations for isolated building with flush vent and short stacks were part of the model. The dilution, defined as the ratio of the exhaust concentration (C_e) to receptor concentration (C_r), for buildings with short stack (less than 3 m), was based on wind tunnel experimental works of Halitsky (1963):

$$D_{\min} = \left[\alpha + 0.11(1 + 0.2\alpha)S/{A_e}^{0.5}\right]^2 \tag{7.5}$$

where:

$D_{\min}$ is the minimum dilution for a given wind speed.
S is the distance between a particular rooftop receptor and the stack (m).
α is a factor, which incorporates building shape and orientation, and M (generally $\alpha = 1$).
A_e is the exhaust area (m^2).

Similarly, the dilution equation for an isolated building with a flush vent was based on the works of Wilson and Lamb (1994), Wilson and Chui (1985, 1987) and Chui and Wilson (1988):

$$D_{\min} = \left[{D_o}^{0.5} + {D_s}^{0.5}\right]^2 \tag{7.6}$$

where:

D_o is the initial dilution caused by the turbulence in the exhaust jet.
D_s is the dilution caused by the atmospheric and building effects.

It may be noted that Eqs. 7.5 and 7.6 did not consider the wake recirculation length (Eq. 7.1) to estimate the dilution. Some earlier studies by Saathoff et al. (1998) and Stathopoulos et al. (1999) have also shown the highly conservative nature of ASHRAE 1997, by comparing the model to field concentration measurements carried out on some of the buildings at Concordia University. This led to the development of the ASHRAE 2003 model as will be also discussed further.

7.2.2.2 Gaussian Dilution Model (ASHRAE 2003, 2007, 2011)

The Gaussian dilution model recommended in ASHRAE 2003 is based on a series of experiments carried out in a water flume by Wilson et al. (1998). The model predicts worst-case dilution at roof level, D_r, assuming that the plume has a Gaussian (bell-shaped) concentration profile in both the vertical and horizontal directions. The effective height of the plume above the roof or rooftop structure is

$$h = h_s + h_r - h_d \tag{7.7}$$

where h_s is stack height, h_r is plume rise and h_d is the reduction in plume height due to entrainment into the stack wake during periods of strong winds. It should be noted that h_s is the height of the stack tip above the roof minus the height of rooftop obstacles (including their recirculation zones) that are in the path of the plume.

Plume rise, which is assumed to occur instantaneously, is calculated using the formula of Briggs (1984):

$$h_r = 3\beta d_e (V_e/U_H) \tag{7.8}$$

where d_e is the stack diameter, V_e is the exhaust velocity, U_H is the wind speed at building height and β is the stack capping factor. The value of β is 1 for uncapped stacks and 0 for capped stacks. The ratio of the exhaust velocity (V_e) to the wind velocity at the building height (U_H) is called exhaust momentum ratio (M). The formulations for plume rise estimate (see Eq. 7.7) has remained unchanged for the 2003 and 2007 versions. However, the 2011 version has implemented the following changes:

$$h_r = \min\{\beta h_x, \beta h_f\} \tag{7.9}$$

where:

h_x and h_f are estimated as

$$h_x = \frac{3{V_e}^2{d_e}^2X}{4{\beta_j}^2{U_H}^2} \tag{7.10}$$

$$h_f = \frac{0.9\left[\left({V_e}^2{d_e}^2/4\right)\left(U_H/U_*\right)\right]^{0.5}}{\beta_j U_H} \tag{7.11}$$

where:

U_* is the friction velocity (m/s).
β_j is the jet entrainment coefficient calculated by

$$\beta_j = \frac{1}{3} + \frac{U_H}{V_e} \tag{7.12}$$

The logarithmic wind profile equation is

$$U_H/U_* = 2.5\ln(H/Z_o) \tag{7.13}$$

where:

Z_o is the surface roughness length (m).

As per ASHRAE 2003, the roof-level dilution for a plume at height h at a receptor distance X from the stack is given as

$$\mathrm{D_r} = 4\frac{\mathrm{U_H}}{\mathrm{V_e}}\frac{\sigma_\mathrm{y}}{\mathrm{d_e}}\frac{\sigma_\mathrm{z}}{\mathrm{d_e}}\exp\left[\frac{\mathrm{h}^2}{2\sigma_\mathrm{z}^2}\right] \tag{7.14}$$

where U_H is the wind speed at the building height, d_e is stack diameter, V_e is the exhaust speed and σ_y and σ_z are the plume spreads in the horizontal and vertical directions, respectively. The equations for σ_y and σ_z are adjusted from a 60 min averaging time to a 2 min averaging time using the 0.2 power:

$$\frac{\sigma_\mathrm{y}}{\mathrm{d_e}} = 0.071\left(\frac{\mathrm{t_{avg}}}{2.0}\right)^{0.2}\frac{\mathrm{X}}{\mathrm{d_e}} + \frac{\sigma_\mathrm{o}}{\mathrm{d_e}} \tag{7.15}$$

$$\frac{\sigma_\mathrm{z}}{\mathrm{d_e}} = 0.071\frac{\mathrm{X}}{\mathrm{d_e}} + \frac{\sigma_\mathrm{o}}{\mathrm{d_e}} \tag{7.16}$$

where t_{avg} is the concentration averaging time in minutes and σ_o is the initial source size that accounts for stack diameter and for dilution due to jet entrainment during plume rise.

It must be noted that Eqs. 7.15 and 7.16 remain unchanged in 2003 and 2007 versions. However, ASHRAE 2011 uses the formulations of Cimoreli et al. (2005) to estimate the spread parameters:

$$\sigma_y = \left({i_y}^2X^2 + {\sigma_o}^2\right)^{0.5} \tag{7.17}$$

$$\sigma_z = \left({i_z}^2X^2 + {\sigma_o}^2\right)^{0.5} \tag{7.18}$$

$$i_y = 0.75i_x \tag{7.19}$$

$$i_z = 0.5i_x \tag{7.20}$$

$$i_x = \left[0.24 + 0.096\log_{10}(Z_o) + 0.016(\log_{10}Z_o)^2\right][\ln(30/Z_o)/\ln(Z/Z_o)] \quad (7.21)$$

where:

i_x, i_y and i_z are the turbulence intensities in x, y and z directions.
σ_o is the initial source size and is set equal to $0.35d_e$ (m).
Z is the height of the building (m).

According to ASHRAE 2011, calculations must be carried out separately for Z_o, $0.5Z_o$ and $1.5Z_o$, and the lowest dilution must be considered for the design. Additionally, following the recommendation of Petersen et al. (2004), dilutions can be estimated on the sidewall of a building based on the dilution obtained on the nearest rooftop receptor, by increasing the latter by a factor of 2 (for conservative values). This is an important contribution of ASHRAE 2011 model, since previous versions can only be used to assess dilutions on the rooftop of the emitting building. The Gaussian dilution model (Eq. 7.14) should not be used when the plume height, h, is less than the maximum height of the roof recirculation zones that are in the path of the plume. The dilution equation used in ASHRAE 2007 and 2011 is

$$D_r = 4(U_H/V_e)\left(\sigma_y/d_e\right)(\sigma_z/d_e)\exp\left(\zeta^2/2\sigma_z^2\right) \quad (7.22)$$

where:

$$\begin{aligned} \zeta &= h - H_c \\ &= 0 \text{ if } h < H_c \end{aligned}$$

ζ is the vertical separation between ‘h’ and H_c.

ASHRAE 2011 also provides a detailed discussion on averaging time effects on near-field dilutions, which is a significant contribution since this was not part of previous versions. It is worth noting that ASHRAE 2011 considers the dilution estimates equivalent to 10–15 min averaging time, while the 2007 version assumes these dilutions to be equivalent to 2 min and considers it to be constant for longer averaging times. However, averaging time greatly influences the dispersion process especially at the micro-scale level, as discussed in Hajra et al. (2011). ASHRAE 2007 limits the value of $\zeta^2/2\sigma_z^2$ to 7, while the 2011 version does not impose any limits, which has led the latter to predict even more conservative estimates compared to ASHRAE 2007 for higher exhaust speeds ($M > 3$), as will be discussed further. Table 7.1 summarises the main features and contributors of each model.

Table 7.1 Summary of various ASHRAE dispersion models and their respective features

Model	[a]Based on the works of	Main features
ASHRAE 1997/1999	Halitsky (1963) Wilson (1979, 1982) Wilson and Lamb (1994) Wilson and Chui (1985, 1987) Chui and Wilson (1988)	Adopts a non-Gaussian approach Presents separate formulae for rooftop stacks and flush vents Assumes the calculated dilutions are for 10 min averaging time
ASHRAE 2003 and 2007	Wilson (1979, 1982) Wilson et al. (1998) Briggs (1984)	Limits $h^2/2\sigma_z^2$ to 5 for ASHRAE 2003 and 7 for ASHRAE 2007, close to the stack Considers σ_y and σ_z to be functions of exhaust diameter and receptor distance Assumes initial spread (σ_o) to be function of M Assumes dilution estimates from Eqs. 7.3 and 7.4 for 2 min averaging time and considers the dilution values to be constant for longer averaging times
ASHRAE 2011	Wilson (1979, 1982) Wilson et al. (1998) Cimoreli et al. (2005) Petersen et al. (2004)	Considers no limit for $h^2/2\sigma_z^2$ close to the stack Assumes σ_y and σ_z to be functions of turbulence intensities and receptor distance Assumes initial spread (σ_o) equal to $0.35d_e$ States explicitly that dilution estimates for ASHRAE 2011 are for 10–15 min averaging time

[a]Only main contributors are mentioned

7.3 Application of Dispersion Models to Near-Field Pollutant Dispersion Problems

Dispersion models are essentially computer-based models that can solve Gaussian equations to assess pollutant concentrations at a given rooftop/ground receptor. The Environmental Protection Agency (EPA), USA, has developed several models that can be applied to various situations (e.g. accidental release, release of pollutants from point or area sources, etc). Most of these models require inputs in the form of meteorological data, rate and type of pollutant releases and receptor locations, while the output is generated as concentrations at specific locations or contour plots. Only some of these models, such as Atmospheric Dispersion Modelling System (ADMS) and SCREEN, have been applied to near-field pollutant dispersion problems, because the majority of them cannot simulate the turbulence caused by buildings and only apply to far-field situations (Hajra et al. 2010). In fact, ADMS is based on the model of Hunt and Robins (1982) and has been validated using several field studies (e.g. Robins and McHugh 2001). However, some recent studies by Hajra et al. (2010) have shown that ADMS cannot model near-field pollutant dispersion, because it assumes a uniform concentration field in the wake of the building. Furthermore, ADMS is incapable of simulating the effect of a rooftop structure (RTS), which can greatly affect plume concentrations on the building roof. According to Riddle et al. (2004), ‘such atmospheric dispersion packages are not able to assess the local effects of a complex of buildings on the flow field and turbulence, and whether gas will be drawn down amongst the buildings’. A detailed description of various EPA models, and their applications to near-field plume dispersion, is discussed in Stathopoulos et al. (2008).

7.4 Application of CFD Models to Near-Field Pollutant Dispersion Problems

CFD has been an emerging tool in the last few decades mainly because of increased cost associated with experimental work, coupled by the development of high-speed computers which can facilitate faster computing methods to solve the complex ‘Navier-Stokes equations’. CFD mainly consists of Reynolds-averaged Navier-Stokes (RANS)-based models (steady and unsteady) and Lagrangian and large eddy simulations (LES). The main problem with the application of CFD for near-field dispersion problems is that they cannot accurately simulate the turbulence caused by buildings and structures (Tominaga and Stathopoulos 2011). In fact studies have also shown that CFD simulations are extremely sensitive to turbulent Schmidt number (Sct) variations (Tominaga and Stathopoulos 2007). According to ASHRAE 2011, ‘Based on the current state of the art, CFD models should be used with extreme caution when modelling exhaust plumes from laboratory pollutant sources. Currently, CFD models can both over- and underpredict concentration levels by orders of magnitude, leading to potentially unsafe designs’. This explains the need to carry out additional experiments (wind tunnel/field) for realistic scenarios and utilise those results to improve CFD in the future. A detailed discussion of CFD is beyond the scope of this chapter. However, one may refer to Stathopoulos (1997) and Blocken et al. (2011) for additional information on the subject.

7.5 Selected Results from Recent Studies

In this section, the results from previous studies are classified in the following sections:

(a) Wind tunnel, ADMS and ASHRAE comparisons
(b) Wind tunnel and ASHRAE dilution results
(c) CFD, wind tunnel and ASHRAE comparisons

7.5.1 Wind Tunnel, ADMS and ASHRAE Comparisons

Figure 7.2a shows comparisons for wind tunnel data, ADMS and ASHRAE 2003 and 2007 for an isolated building without an RTS, with a centrally placed stack of 1 m and M = 3, in terms of normalised dilution. The building used in this study was 15 m high and 50 m square in plan; additional experimental details can also be found in Stathopoulos et al. (2008). Results show that ADMS predicts about five times higher dilutions than wind tunnel data at all receptors beyond 5 m from the stack. This is primarily because ADMS assumes a uniform concentration distribution in the wake of the building. ASHRAE 2003 and 2007 predict comparable dilutions at all receptors, although both models predict about ten times lower dilutions than wind tunnel data. This is because ASHRAE predicts lower plume rise, resulting in higher rooftop concentrations (lower dilutions) at all receptors. The trends are somewhat different for the same building with an RTS, as shown in Fig. 7.2b, where ASHRAE 2007 predicts about five times lower dilutions than wind tunnel data at all receptors due to reasons explained previously. However, ASHRAE 2003 predictions are about five times higher than wind tunnel data because the value of the exponential term in the 2003 version is limited to 5, while ASHRAE 2007 limits this value to 7 (Table 7.1). In fact, ASHRAE 2007 and ADMS compare well at almost all points, except at receptors close to the downwind edge of the building. It may be mentioned that ADMS cannot model the effects of an RTS, and, therefore, only results for building with flat roof are presented for comparisons.

7.5.2 Wind Tunnel and ASHRAE Dilution Results

Figure 7.3a shows wind tunnel dilutions on the rooftop of the low building in the presence of a taller upstream building, for hs = 1 m and M = 1, and compares them

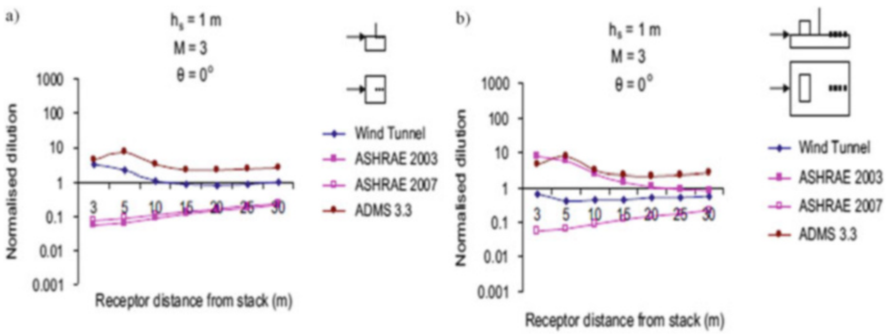

Fig. 7.2 Normalised dilution on rooftop of low building: (**a**) without RTS and (**b**) with RTS (Hajra et al. 2010)

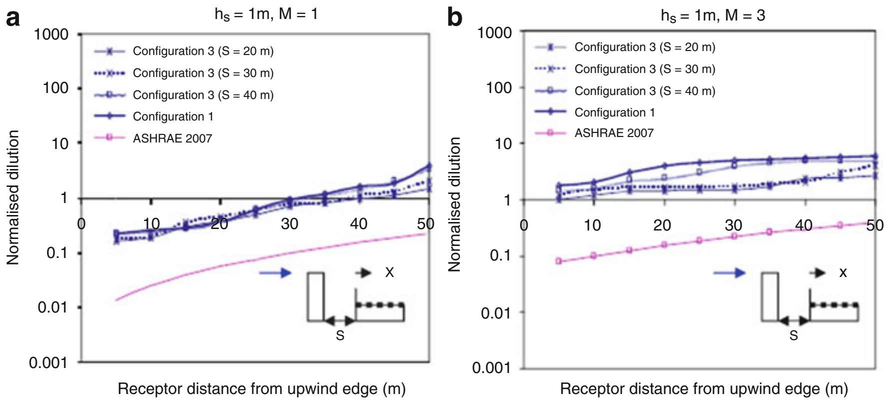

Fig. 7.3 Normalised dilution on rooftop of low building for X = 0: (**a**) M = 1; (**b**) M = 3 (Hajra et al. 2011)

to ASHRAE 2007. Configuration 3 consists of a taller upstream building, while Configuration 1 is an isolated low building. The spacing between buildings was varied from 20 to 40 m. The low-emitting building was 15 m high, and the upstream building was 30 m high. Both buildings were of 50 m across wind dimension. Additional experimental details can be obtained from Hajra et al. (2011). Results show that at M = 1 the wind tunnel dilutions are comparable at all receptors for different spacing. However, at M = 3 the dilutions are comparable only at S = 20 m and S = 30 m (Fig. 7.3b). As the distance increases further to S = 40 m, the dilutions obtained from Configuration 3 become comparable to the isolated case. This is because the plume is no longer engulfed within the recirculation length of the upstream building. ASHRAE (2007) predicts lower dilutions for both configurations and can be applied only for the isolated case. Additionally, the formulations do not incorporate the effects of spacing between buildings.

Figure 7.4 presents comparisons for wind tunnel data from Gupta et al. (2012), Wilson et al. (1998), Schulman and Scire (1991) and ASHRAE (2003, 2007, 2011) models. Wind tunnel data from Gupta et al. (2012) correspond to a low-rise building (15 m high) in an urban terrain, while results from Wilson et al. (1998) and Schulman and Scire (1991) correspond to results for a suburban terrain for a low-rise building of 12 and 15 m, respectively. Generally, the experimental findings from Gupta et al. (2012), Wilson et al. (1998) and ASHRAE (2003) compare well at receptors 20 m beyond the stack, while the data from Schulman and Scire (1991) are somewhat higher (about a factor of 5) than the results from Gupta et al. (2012) due to the difference in experimental conditions used in the two studies. However, ASHRAE 2007 and 2011 predict ten times lower dilutions than wind tunnel data from Gupta et al. (2012), indicating the unsuitability of both models.

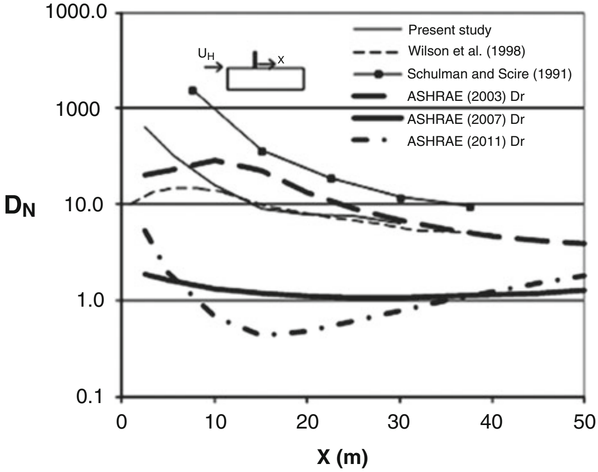

Fig. 7.4 Model validation with concentration data from previous studies for the low-rise building with no rooftop structure for $h_s = 3$ m, and $\theta = 0°$ (Gupta et al. 2012)

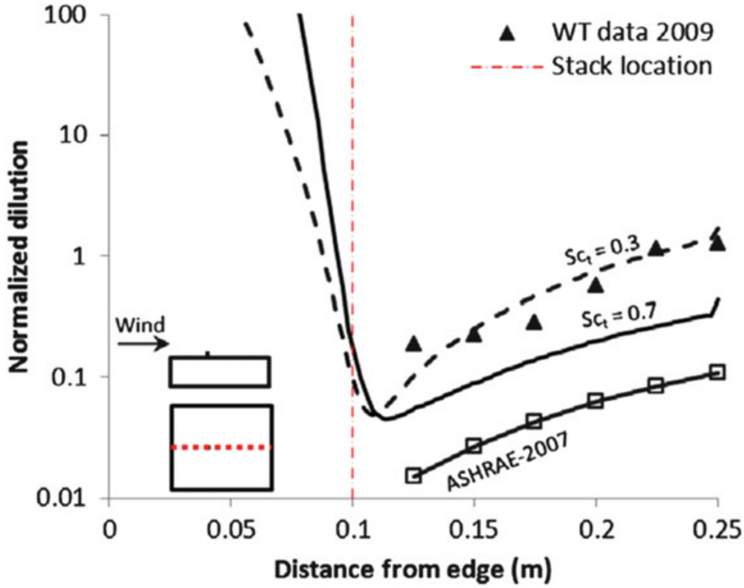

Fig. 7.5 Normalised dilution on isolated building roof for different Sc_t (Chavez et al. 2012)

7.5.3 CFD, Wind Tunnel and ASHRAE Comparisons

Figure 7.5 shows comparisons for wind tunnel data, CFD for Sct values of 0.3 and 0.7 (realisable k-ε model) and ASHRAE 2007 in terms of normalised dilutions for an isolated building with stack height 1 m and M = 1. The building was tested in the boundary layer wind tunnel at Concordia University for an urban terrain (experimental details can be found from Hajra et al. (2010)). Sct is essentially the ratio of the kinematic viscosity to mass diffusivity. Results show that for the centrally located stack, wind tunnel data and CFD compare well for Sct = 0.3 at receptors beyond the stack. However, CFD results are lower than experiment by a factor of 5 for Sct = 0.7 at all receptors, indicating the sensitive nature of the CFD model to changes in Sct. ASHRAE 2007 predictions are overly conservative since the values are lower than wind tunnel data by about 10 times. Interestingly, CFD also predicts dilutions upwind of the stack unlike wind tunnel data, possibly because in the latter case, the instrument cannot detect concentrations of such low value (high dilutions) upwind of the stack. The general behaviour of CFD and ASHRAE suggests that both models must be investigated in detail using experimental data for realistic urban layouts, for future improvements.

7.6 Design Guidelines

The following provides a summary of various design guidelines formulated on the basis of results obtained from some past and very recent studies:

7.6.1 Design Guidelines Based on Field Studies

Field studies were conducted on two of the buildings at Concordia University campus. Tracer gas was released from a low-emitting building, in the presence of a taller upstream building. It was found that the plume was engulfed within the recirculation region of the upstream building, causing the plume to travel towards the leeward wall of the upstream building. This increased the concentrations on the rooftop of the low-emitting building, besides affecting the leeward wall of the taller upstream building. This is one of the most important field studies in the area of near-field pollutant dispersion, since most previous studies were either performed in the wind tunnel for isolated buildings or were focussed on urban air quality modelling for far-field problems. Additional experimental details can be found in Stathopoulos et al. (2004). This subsection describes some of the design guidelines that can be employed for a taller upstream building.

7.6.1.1 Stack Location

For open fetch situations, it is better to place the stack near the centre of the roof. In this way, the leading edge recirculation zone is avoided, thus maximising plume rise. In addition, the required plume height to avoid contact with leeward wall receptors is minimised. For the case of a taller building upwind of the emitting building, the centre of the roof may not be the optimum stack location for receptors on the emitting building. Concentrations over most of the roof can be reduced by placing the stack near the leading edge. However, this stack location will result in higher concentrations on the leeward wall of the adjacent building. Naturally, this depends on the distance between the two buildings.

7.6.1.2 Stack Height

For open fetch situations, increasing the stack height from 1 to 3 m reduces concentrations near the stack by approximately a factor of 2. Far from the stack ($x > 20$ m), the effect is negligible. A stack height of at least 5 m is required to provide significant reduction of concentration at such distances. For an upwind adjacent building, small changes in stack height have little effect on concentration.

7.6.1.3 Stack Exhaust Speed

Increasing stack exhaust speed by a factor of 2.5 reduces concentrations near the stack by the same factor. For distant receptors ($x > 20$ m), the effect of exhaust speed depends on the M value (the ratio of exhaust speed to wind speed). In the low M range ($1.5 < M < 4.5$), which is typical of wind speeds exceeding 5 m/s, increasing exhaust speed may not be beneficial for distant receptors because the plume rise may not be sufficient to avoid them. On the other hand, for light wind conditions, doubling the exhaust speed may cause M to be high enough so that concentrations are reduced over the entire roof.

7.6.2 Design Guidelines Based on More Recent Studies

More recent studies on the effects of taller upstream configurations and taller downstream configurations have certainly shed more light on the problem of pollutant re-entry into buildings (Hajra et al. 2011; Hajra and Stathopoulos 2012). These studies were performed in the boundary layer wind tunnel at Concordia University, Canada, for two separate cases – upstream building configurations and downstream building configurations. In this context, the building dimensions, flow parameters, wind direction and speed, stack location and height and spacing between buildings were varied. Therefore, this was a more comprehensive study as opposed to the field study at Concordia and limited studies by Wilson et al. (1998). For taller upstream configurations, with wind approaching from the direction of the taller building:

(a) Intakes on emitting building should be placed on its leeward wall if possible.
(b) Intakes should not be placed on leeward wall of upwind building.

According to Hajra et al. (2011), 'When a stack is placed at the upwind edge of the emitting building that lies within the recirculation zone of the upstream

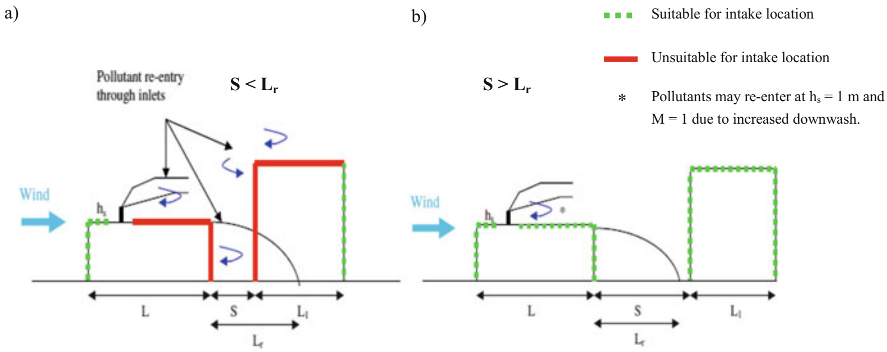

Fig. 7.6 Schematic representation for suitability of intake location at various building surfaces for (**a**) $S < L_r$ and (**b**) $S > L_r$ (Hajra and Stathopoulos 2012)

building, intakes should not be located close to the stack; although they may be placed closer to the leeward wall of the emitting building. For such cases, high stacks and high M values should be used to avoid stack downwash effects'. In general, when a low-emitting building lies within the recirculation zone of a taller upstream building, intakes must be avoided upwind of centrally located stacks, since these locations have high pollutant concentrations due to the geometry of the plume.

Similar guidelines for the safe placement of stack and intakes are also provided for downstream building configurations, as shown in Fig. 7.6 (Hajra and Stathopoulos 2012). Results show that when the downstream building lies within the recirculation zone of the emitting building, intakes should be avoided on building surfaces downwind of the stack (Fig. 7.6a). However, when the downstream building lies beyond the recirculation region of the emitting building, intakes may be safely placed on any building surface (Fig. 7.6b).

7.7 Conclusions

The following conclusions may be drawn from this chapter:

- Dispersion models such as ADMS are more suited for far-field dispersion problems because they cannot model the turbulence caused by buildings and RTS, which greatly influence near-field pollutant dispersion.
- ASHRAE 2003 and 2007 versions were found to be overly conservative for most isolated building cases, while the 2011 version was found to be suitable only for some cases ($M < 3$). In general, all ASHRAE versions are not capable of simulating the effects of adjacent buildings, local topography and rooftop structures.

- CFD cannot simulate the turbulence caused by the building, and, hence, further investigations are required to improve this methodology. In particular, the results are very sensitive to Sct values. Generally, lower values of Sct resulted in comparable dilutions with wind tunnel data for an isolated building.
- Design guidelines from Hajra et al. (2011) and Hajra and Stathopoulos (2012) for the safe placement of stack and intake for upstream and downstream building configurations are a significant contribution in the area of near-field pollutant dispersion studies.

The results obtained are encouraging because they demonstrate the general adequacy of the wind tunnel data to represent real design situations and the limitations of the ASHRAE and ADMS models to predict real dilutions for particular building configurations and stack locations. Dispersion models like ADMS can be improved further, if the formulations used by these models incorporate the effects of wake recirculation region of a building, besides turbulence caused by an RTS and neighbouring buildings. The design guidelines provided in this paper will be helpful to building physicists and practising engineers to tackle a multifaceted complicated problem, for which codes and standards are either mute or extremely general to apply to particular real conditions. It is understandable that additional wind tunnel studies representing a more realistic urban scenario must be conducted to improve future versions of ASHRAE model.

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