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Chemical and Biological Hazard Prevention

Studies and Research Projects

REPORT **R-848**

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A Wind Tunnel Study of the Effect of Adjacent Buildings on Near-Field Pollutant Dispersion from Rooftop Emissions

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PEER REVIEW

In compliance with IRSST policy, the research results published in this document have been peer-reviewed.

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ABSTRACT

The dispersion of pollutants from rooftop emissions within the boundary layer is greatly influenced by buildings and local topography. It is thus very difficult to make accurate assessments of plume concentrations on various building surfaces. Pollutants released from a rooftop stack can cause potential health hazards to building occupants by re-entering the building from which they are released or by entering a neighbouring building through openings on building surfaces. Most studies in the past have focussed on rooftop emissions from isolated buildings, which seldom exist in the urban environment. A majority of dispersion models are incapable of providing reasonable dilution estimates on building surfaces and do not incorporate the effect of adjacent buildings. Therefore, there is a need to develop a new model or modify an existing model to take into account the effects of dispersion of effluents and focus on the impact of buildings that are in close proximity with the source of pollutants. To address this issue, a collaborative research program between Concordia University and IRSST was elaborated relying on both experimental and numerical modeling. This report presents the experimental findings while the numerical findings are published in a companion report[1] (Bahloul *et al.* 2014).

The experimental modeling consisted of performing tracer gas studies in the Boundary Layer Wind Tunnel at Concordia University for various adjacent building configurations. These configurations include buildings of different geometries placed upstream (or downstream) of the emitting building (source). Another configuration consisting of a building placed upstream and another building placed downstream of the source was also studied. In this regard, various parameters that include: building dimensions, spacing between buildings, stack height and location; exhaust parameters and wind azimuth were varied. These results were compared to the Gaussian based ASHRAE 2007 and 2011 models.

Results from the wind tunnel data indicate that an emitting building placed within the recirculation length of a taller upstream building produces lower dilutions on the roof of the emitting building. Similarly, taller downstream buildings disallow the plume from spreading thereby increasing plume concentrations on the roof and leeward wall of the emitting building. In general, spacing between buildings and exhaust speed were found to be critical parameters influencing the plume characteristics. Based on the experimental data, design guidelines for the safe placement of stack and intake on various building surfaces are also presented. ASHRAE 2007 predictions are overly conservative, while ASHRAE 2011 predictions compare well with wind tunnel data for the isolated building for low exhaust momentum ratios (M) of less than 3. Rectifications to the ASHRAE 2007 model are also presented to obtain reasonable dilution estimates for the isolated case, besides incorporating the effects of adjacent buildings. The rectified ASHRAE 2007 model was found to perform well for most cases when compared to results obtained from present and previous studies.

[1] http://www.irsst.qc.ca/media/documents/PubIRSST/R-849.pdf

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NOMENCLATURE

Symbol	Definition	Units
A_e	Stack area	m^2
B_1	Distance dilution parameter	-
B_s	Smallest dimension of building face normal to wind	m
B_L	Largest dimension of building face normal to wind	m
C_e	Exhaust concentration	ppm
C_r	Receptor concentration	ppm
D_o	Initial dilution	-
D_d	Dilution on roof of the downstream building	-
D_{de}	Dilution on downwind edge of low building	-
D_{min}	Minimum dilution (C_e/C_r)	-
D_{lu}	Dilution on leeward wall of the upstream building	-
D_{le}	Dilution on the leeward wall of the low building	-
D_r	Dilution at roof level (C_e/C_r)	-
$(D_r)_s$	Dilution estimated for a shorter averaging time	-
$D_{normalised}$	Normalised dilution	-
D_i	Dilution on roof of isolated building	-
D_a	Dilution on roof of low building for adjacent building configurations	-
D_{wd}	Dilution on windward wall of downstream building	-
d_e	Stack diameter	m
f1	Factor which relates roof dilution of isolated and adjacent building configurations	-
f2	Factor which relates dilutions on roof of the downstream and downwind edge of the low building	-
f3	Factor which relates the dilution downwind of stack and the dilution on the leeward wall of upstream building	-
f4	Factor which relates the dilutions on downwind edge of low building and on leeward wall of low building	-

Symbol	Definition	Units
f5	Factor which relates dilutions on windward wall of downstream building and downwind edge of low building	-
h	Height of the low building	m
h_1	Height of the upstream building	m
h_2	Height of the downstream building	m
h_d	Reduction in plume height	m
h_{plume}	Height of plume	m
h_r	Plume rise (ASHRAE 2003, 2007)	m
h_x, h_f	Plume rise (ASHRAE 2011)	m
h_s	Stack height	m
h_{small}	Smallest plume height	m
h_{top}	Height of critical recirculation zone	m
H_c	Maximum height of the roof recirculation zone	m
H	Height of the building	m
$I_u(z)$	Turbulence intensity at a given height z	-
i_x, i_y, i_z	Turbulence intensity in x, y, z directions	-
k	Von Karman constant = 0.4	-
L	Along wind dimension of the low building	m
L_1	Along wind dimension of the upstream building	m
L_2	Along wind dimension of the downstream building	m
L_c	Length of the roof recirculation zone	m
L_r	Length of the building wake recirculation	m
m_i	Measured dilution at a given receptor	-
M	Exhaust momentum ratio (V_e/ U_H)	-
n	Total number of sampling points (receptors)	-
p_i	Predicted dilution at a given receptor	-
Q_e	Volumetric flow rate	m^3/s
S_1	Distance between low building and upstream building	m
S_2	Distance between low building and downstream building	m

Symbol	**Definition**	**Units**
Sc_t	Turbulent Schmidt number	-
t_s	Averaging time	min
u_*	Friction velocity	m/s
U_H	Wind velocity at building height	m
V_e	Exhaust velocity	m/s
$V(z)$	Velocity of wind at height z	m/s
V_g	Gradient velocity	m/s
w	Across wind dimension of the low building	m
w_1	Across wind dimension of the upstream building	m
w_2	Across wind dimension of the downstream building	m
x	Receptor distance from upwind edge	m
x'	Receptor distance from edge of downstream building	m
X_s	Stack location from upwind edge	m
X_c	Distance from the leading edge to H_c	m
z	Height of the building above the ground	m
Z_o	Roughness length	m
Z_2	High turbulence region	-
Z_3	Roof wake boundary	-
Z_g	Gradient height	m

LIST OF SYMBOLS AND ABBREVIATIONS

Greek symbol	Definition	Units
σ_o	Initial source size of the plume	m
σ_y	Spread parameter (horizontal direction)	m
σ_z	Spread parameter (vertical direction)	m
α	Power law exponent	-
β	Stack capping factor	-
β_j	Jet entrainment coefficient	-
ζ	Vertical separation (h_{plume} - H_c)	m
ρ_e	Density of exhaust	kg/m^3
ρ_a	Density of air	kg/m^3
θ	Wind azimuth	degrees

Abbreviations

ASHRAE	American Society of Heating Refrigeration and Air conditioning Engineers
ADMS	Atmospheric Dispersion Modelling System
CFD	Computational Fluid Dynamics
EPA	Environmental Protection Agency
ESDU	Engineering Science Data Unit
GC	Gas Chromatograph
LES	Large Eddy Simulation
rmse	root mean square error
RTS	Roof Top Structure

1. INTRODUCTION

1.1 Background

Air pollution is a global phenomenon and a cause for concern amongst engineers and health physicists. In particular, pollutant flow within building arrays in urban areas is a complex process since the flow is governed by turbulence due to atmospheric conditions, local topography and buildings. Pollutants released from a rooftop stack of a building can re-enter the building or enter a neighbouring building thereby deteriorating the indoor air quality (Petersen *et al.* 2002). People working at universities and industrial laboratories that release toxic fumes are more prone to potential health problems due to re-ingestion of pollutants. Unfortunately, most current design standards are not fully equipped to address this issue. Therefore, it is necessary to carry out a thorough investigation to understand the air and pollutant flow around buildings, and develop a suitable technique to alleviate the problem of re-ingestion.

The effects of adjacent buildings on near-field pollutant dispersion have been studied by very few researchers. Nevertheless, Stathopoulos *et al.* (2004) found, through field studies, that a taller upstream building produces higher rooftop concentrations on a lower emitting building. Furthermore, pollutant concentrations were found to be higher on the windward wall of a downstream building when pollutants were released from an emitting building placed upstream (Wilson *et al.* 1998). There are also plenty of studies on rooftop emissions from isolated buildings, a situation which seldom exist in an urban environment (Halitsky, 1963). Therefore, the present study on adjacent building effects on near-field pollutant dispersion represents a more realistic case and is extremely important.

In the past, there have been many collaborative research projects carried out by the Institut de recherche Robert-Sauvé en santé et en sécurité du travail (IRSST) and Concordia University. These include field tracer studies carried out on some of the buildings on the Concordia University campus, and simulation of these results at the Boundary Layer Wind Tunnel (BLWT) at Concordia University (Stathopoulos *et al.* 2004). An investigation of various Environmental Protection Agency (EPA) and American Society of Heating, Refrigeration and Air-conditioning Engineers (ASHRAE) models was also carried out to assess the suitability of these models for near-field dispersion problems (Stathopoulos *et al.* 2008). This report summarises the experimental findings of various adjacent building configurations that were tested in the BLWT. The wind tunnel data were also compared to ASHRAE 2007 and 2011 models. Based on the results, suggestions to improve ASHRAE modelling techniques, as well as design guidelines for the safe placement of stack and intake on various building surfaces to avoid plume re-ingestion are presented. The subsequent section describes the objectives of the present study.

1.2 Objectives of the proposed research

The present study includes the following objectives:

1. Carrying out extensive tracer gas studies in the BLWT at Concordia University, for various adjacent building configurations which include:

   i) Isolated building (source);

   ii) Buildings of different geometries placed upstream of the source;

   iii) Buildings of different geometries placed downstream of the source;

   iv) One building placed upstream and another building placed downstream of the source.

2. Understanding the various parameters that influence plume characteristics for adjacent building configurations. These parameters include: stack height and location, dimensions of buildings, spacing between buildings, exhaust speed, wind speed and azimuth.

3. Comparing the wind tunnel estimates to ASHRAE models (2007 and 2011) for various adjacent building configurations.

4. Suggesting ways to improve the ASHRAE model for isolated buildings as well as to incorporate the effects of adjacent building configurations to get reasonable dilution estimates.

5. Providing design guidelines for safe placement of stack and intake on various building surfaces.

As previously mentioned, this report presents primarily experimental findings, while applications of Computational Fluid Dynamics (CFD) models on experimental results from the present study are included in a companion report (Bahloul *et al.* 2014). The present report is divided into seven chapters. Following the introduction in this Chapter, a detailed literature review is presented in Chapter 2, which describes previous studies carried out in the area of near-field plume dispersion. Chapter 3 describes the wind tunnel experimental technique, followed by results and discussion in chapter 4. Chapter 5 presents rectifications to improve ASHRAE models, while guidelines for the safe placement of stack and intakes on various building surfaces are presented in Chapter 6. Conclusions and recommendations for future work are presented in Chapter 7, followed by a list of references and appendices.

2. LITERATURE REVIEW

2.1 General

Pollutants released from rooftop stacks can re-enter the building if the location of intakes is not properly designed. Effluents entering a building can cause potential health problems to the people residing in them (Petersen *et al.* 2002). The majority of studies have focussed on exhausts released from isolated building (Halitsky, 1963; Wilson, 1979) with very few studies on adjacent building effects (Stathopoulos *et al.* 2008).

A brief description of air and pollutant flow around an isolated building and adjacent building configurations is presented in section 2.2. Following this, literature on experimental work, which includes field and wind tunnel studies are described in section 2.3. Some recent literatures pertaining to the application of CFD models followed by the application of a few Gaussian based models are presented in sections 2.4 and 2.5 respectively. A summary of this chapter is presented in section 2.6.

2.2 Air and pollutant flow past buildings

At the outset, the air and pollutant flow around an isolated building is described. Through extensive experimental studies Wilson (1979) showed that when pollutants were released from a rooftop stack, three different zones are formed. At the upwind edge of the building a roof recirculation region (Z_1) forms where flow separation occurs and, due to the low exhaust speeds, some part of the effluent may also get trapped within this region. Gradually closer to the stack a high turbulence zone (Z_2) exists where the turbulence due to the stack is higher; concentrations of gas are generally found to be higher in this region. A roof wake boundary (Z_3) forms at a distance sufficiently away from the stack. In this region stack downwash may occur as the pollutants may accumulate at low exhaust speeds and high wind velocities. Wilson suggested that two recirculation lengths form as a result of the air flow around the building:

a) L_c on the roof of the building

b) L_r on the wake of the building

The former was formed when the length of the building was sufficiently long. Wilson's studies showed that a triangular shaped plume (in two dimensions) formed with the sides at 5:1 from the plume centre line. These findings were validated by subsequent studies, including Wilson and Winkel (1982) and Wilson (1983) for various isolated buildings. These results were used in the development of the ASHRAE model in 1999 and subsequent versions published in 2003, 2007 and 2011.

An extension of this study was carried out by Wilson *et al.* (1998) at the University of Alberta to assess the plume structure in the presence of an upstream building. Their study showed that the recirculation cavity that forms in the wake of the upstream building played a major role in altering the plume geometry. A taller upstream building has a tendency to draw the plume towards itself. This was an important finding since the plume trajectory in the presence of an upstream building was not well understood prior to this study. Later, field measurements carried out at two of the buildings of Concordia University also supported this finding (Stathopoulos *et al.* 2004). This study was also extended to assess the plume structure in the presence of a downstream building, and the results showed that a major portion of the plume escaped as “side-leakage” through the sides of the building.

Additionally, some part of the plume could also affect the roof of the downstream building especially if the buildings were sufficiently close to each other. Although Wilson’s studies were very useful to understand the plume geometry it was not sufficient to provide design guidelines for safe placement of stack and intake on building surfaces. A more recent study on the air and pollutant flow around multiple building configurations, by Hajra *et al.* (2013) provides an excellent description of the flow characteristics in a more realistic urban scenario.

2.3 Experimental studies on near-field plume dispersion

In the early sixties Halitsky (1963) performed a series of wind tunnel tracer tests using a cubical block with a flush vent. Based on experimental results, he was able to show that a “return flow” in the wake of the building was formed, which caused some part of the plume to re-enter through openings on the leeward wall. Using these results, he formulated the following equation for minimum dilution:

$$D_{min} = [\alpha + 0.11(1+ 0.2\ \alpha)\ S/A_e^{0.5}]^2 \qquad (2.1)$$

where D_{min} is the dilution at a given receptor, and is defined as a ratio of the exhaust to receptor mass concentration, S is the distance from the source, A_e is the exhaust area and α is the parameter that depends on the building shape, momentum ratio and building orientation, which is dimensionless; hence equation 2.1 is also dimensionless.

In 1985, Wilson and Chui developed an empirical model by performing extensive wind tunnel experimentation on isolated buildings, which they later modified (Wilson and Chui, 1987). They suggested the following expression for the minimum dilution along the plume centre line:

$$D_{min} = (D_o^{0.5} + D_d^{0.5})^2 \qquad (2.2)$$

where D_o is the initial dilution at the exhaust location and D_d is the distance dilution which is produced by both atmospheric and building generated turbulences.

An attempt to understand the effect of adjacent buildings was carried out by Wilson *et al.* (1998). The most significant contribution of this study was to determine the plume structure for upstream and downstream building configurations. Saathoff *et al.* (2009) showed that a Roof Top Structure (RTS) greatly influences the plume dispersion characteristics on the rooftop of a building. Wind tunnel tests were carried out for low and high-rise buildings for different stack heights, exhaust velocities, wind azimuth and RTS locations. In particular, the downwash caused by placing the stack downwind of the RTS was studied. It was found that a RTS reduced rooftop dilutions as compared to buildings with flat roof. However, the present study does not consider the effect of RTS, as all the buildings considered have flat roofs. Future tracer dispersion studies on adjacent building effects that include the effect of RTS would be an interesting endeavour.

Recent wind tunnel studies by Hajra *et al.* (2011, 2013) have shown that when adjacent buildings are spaced away from the emitting building recirculation region, the air and pollutant flow characteristics are similar to that of an isolated building. Most experimental studies initially focussed on understanding the plume structure from rooftop emissions of an isolated building. Gradually, the effect of neighbouring buildings on near-field pollutant dispersion became a subject of discussion amongst researchers.

2.4 Application of CFD models

CFD mostly consists of the Lagrangian, Reynolds Averaged Navier Stokes (RANS) and Large Eddy Simulation (LES) models. There are many wind tunnel and CFD studies on pollutant dispersion in street canyons (e.g. Meroney *et al.* 1996; Wedding *et al.* 1977; Chang and Meroney, 2000, 2001, 2003; Meroney, 2010). Since the present report pertains to experimental findings of numerous multiple-building configurations tested in the wind tunnel, only very limited information on application of CFD models is given here.

Blocken *et al.* (2008) simulated the results obtained from a field study at Concordia University (see Stathopoulos *et al.* 2004, for details) using Reynolds Stress Model (RSM) and compared them to the ASHRAE 1999 model. Their results showed that the turbulent kinetic energy profiles had unintended stream-wise gradients in the computational domain, leading to computational error in the RSM model. Additionally, ASHRAE 1999 results were found to be overly conservative.

The application of different k-ε based turbulence models on pollutant dispersion around an isolated cube was studied by Tominaga and Stathopoulos (2009). They found that "*revised k–ε models provided concentrations in better agreement with the experimental data.*" Additionally, the authors also stated that "*concentrations predicted by all CFD models were less diffusive than those of the experiments.*" Chavez *et al.* (2011) performed CFD simulations using a realisable k-ε model and compared his data to ASHRAE 2007 and wind tunnel data collected from the rooftop of a low building, in the presence of adjacent buildings. Their simulations showed that the results were dependent on the turbulent Schmidt number (Sc_t) values and that it was very difficult to generalise a particular value of Sc_t. ASHRAE results were found to be overly conservative for all building configurations.

More recently, Chavez *et al.* (2012) compared CFD and wind tunnel data for taller upstream building configurations. The simulations were carried out using the realisable k-ε model. According to this paper, "*Some discrepancies between CFD and wind tunnel data were found, specifically for extreme configurations, e.g. significantly taller upstream building. These differences are mainly due to the inherent unsteady fluctuations in the wake of buildings which are not detectable by RANS*". This shows that CFD has certainly been an emerging tool to assess plume dispersion in the built environment. However, additional experimental studies must be used to validate CFD results to improve the latter.

2.5 Application of Gaussian based models

This section presents literature findings on the application of Gaussian based models such as ASHRAE, and EPA models like the Atmospheric Dispersion Modelling System (ADMS).

2.5.1 ADMS

Atmospheric Dispersion Modelling System (ADMS) is a dispersion model which is based on the model developed by Hunt and Robins (1982). It is used to calculate plume concentrations on rooftop or ground level receptors from isolated stacks and rooftop stacks. However, in case of multiple building complexes the model combines them into a single building. A more rigorous study carried out by Stathopoulos *et al.* (2008) showed that ADMS is only useful for estimating plume concentrations several kilometres away from the source and cannot simulate the effects of RTS.

2.5.2 ASHRAE models

The ASHRAE model was first developed using the model of Halitsky (1963). Thereafter, the model has undergone many changes in its formulations due to the works of Wilson, described previously. In 2003, a new model, based on the works of Wilson (1979) was introduced which was further modified in 2007. Studies by Saathoff *et al.* (2009) showed that ASHRAE 2003 and 2007 estimates were highly conservative and cannot be used for stack design. A more recent version was introduced in 2011, which was also found to be overly conservative for some cases (Gupta *et al.* 2012). For a comprehensive review of other available Gaussian models – see Holmes and Morawska (2006).

2.6 Summary

From this chapter, it is understood that there have been several wind tunnel studies but only a limited number of field tests due to the ease in controlling several parameters in the former compared to the latter. There were a few studies, by Wilson and his associates, on the effect of adjacent buildings on near-field pollutant dispersion (Wilson and Netterville, 1976; Wilson *et al.* 1998), but these studies did not systematically vary different parameters (e.g. stack height and location, spacing between buildings, building dimensions etc.), as in the present study. In the future it will be necessary to carry out additional experimental work to study the effect of adjacent buildings on near-field dispersion for more realistic scenarios; a CFD approach would be quite attractive in such cases. Therefore, additional collaboration is required between experimentalists and numerical scientists to improve CFD simulations.

3. METHODS

3.1 General

This report summarises the findings of the experimental study carried out at the Boundary Layer Wind Tunnel (BLWT) at Concordia University. Therefore, it is necessary to understand the wind tunnel modelling technique and the various instruments that were used in performing tracer gas studies. Section 3.2 describes the experimental set up while section 3.3 presents scaling considerations. Section 3.4 on Qualitative analysis, describes the various configurations and results from flow visualisation.

3.2 Wind tunnel experimental set up

The BLWT is an open circuit wind tunnel of 1.8 m square in section and 12.2 m in length (see Appendix B). A thick atmospheric boundary layer was generated using spires, which act as vortex generators and coarse roughness elements. The roughness elements consisted of 5 cm cubes that were staggered and spaced about 6 cm from each other. A cobra probe, whose accuracy of measurement is generally within ± 0.5 m/s up to turbulence intensity values of about 30% (Turbulent Flow Instrumentation, 2008), was used to measure velocity and turbulence intensities. The wind tunnel velocity and turbulence profiles were also compared to results from Engineering Science Data Unit (ESDU 1974) for an urban terrain (Figure 3.1). Good comparisons of normalised wind velocities (V/V_g) from experimental data and ESDU 1974 were obtained very close to the ground and at about 70 cm from the wind tunnel floor. At points between 10 and 60 cm, ESDU estimates are about 1.2 times higher than wind tunnel data.

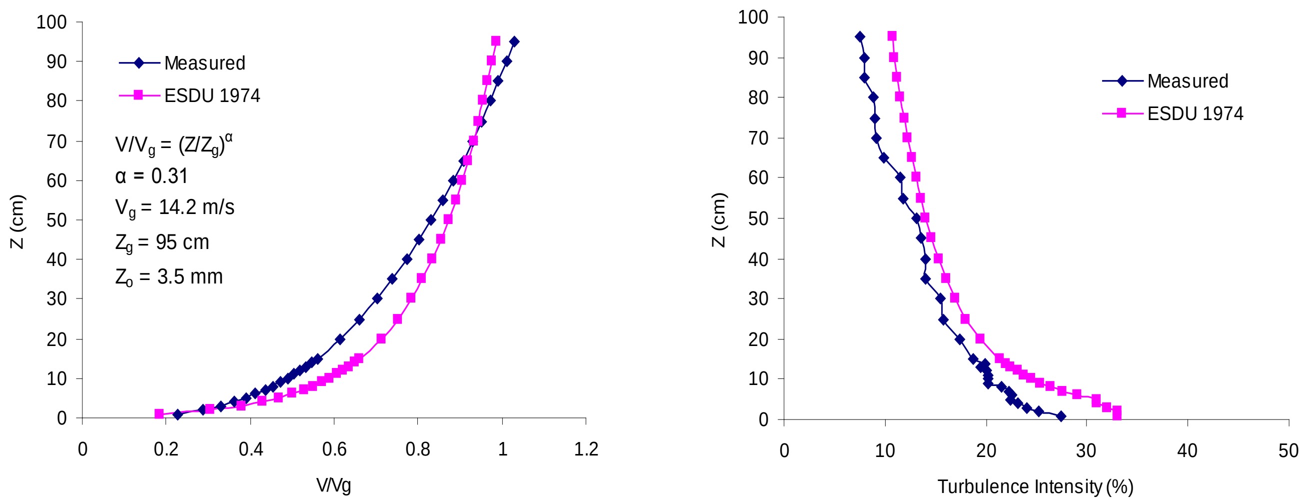


Figure 3.1 – Normalised wind velocity and turbulence intensity profiles measured at the Boundary Layer Wind tunnel of Concordia University (after Hajra and Stathopoulos, 2012).

Similarly, ESDU turbulence estimates are about a factor of 1.3 higher than wind tunnel data at all points. According to Liu *et al.* (2003) the formulations of ESDU 1974 were developed *"by* *correlating strong wind atmospheric data over a large variety of different roughness conditions*". This explains the discrepancy between experimental data and ESDU 1974 for velocity and turbulence profiles for the present study. The different boundary layer characteristics measured in the wind tunnel are presented in Table 3.1.

Table 3.1 – Boundary layer characteristics.

Boundary layer characteristic	Value (wind tunnel scale)
Friction velocity (U*)	1 m/s
Roughness length (Z_o)	3.5 mm
Gradient height (Z_g)	95 cm
Power law exponent (α)	0.31
Gradient velocity (V_g)	14.2 m/s
Turbulence length scale (L_u^x)	40 cm
Wind speed at building height (U_H)	6.2 m/s

Experiments were conducted by releasing tracer gas consisting of a mixture of sulphur hexafluoride (SF_6) and nitrogen from a stack whose diameter was 3 mm, representing a full-scale value of 0.6 m. Tracer experiments started only when the wind tunnel was stable after about 4 minutes of operation.

3.3 Scaling considerations

The building models were constructed of wood on a scale of 1:200. An urban terrain with power law exponent of 0.31 was obtained. The turbulence length scale of 40 cm, which represents a full scale value of 80 m, was found from the expression developed by Counihan (1975).

According to Snyder (1981), the following criteria are necessary to model non buoyant plume dispersion in a wind tunnel. These include:

- Geometric similarity;
- Building Reynolds number > 11000;
- Stack Reynolds number > 2000;

  Tracer studies performed by Saathoff *et al.* (1995) show that "*it is generally not possible to satisfy the stack Reynolds number for small diameter stacks and it is also difficult to trip the flow for such stacks*". In the present study, although the stack Reynolds number was 1900, which is somewhat less than 2000, this did not affect the accuracy of the concentration measurements as explained in Saathoff *et al.* (1995) and Hajra *et al.* (2010).

- Similarity of wind tunnel flow with atmospheric surface layer;

  This refers to similar velocity and turbulence intensity profiles obtained in full scale for wind tunnel measurements.

- Equivalent exhaust momentum ratio.

  In general, exhaust momentum ratio (M) is defined as:

$$M = (\rho_e / \rho_a)^{0.5} (V_e / U_H) \tag{3.1}$$

where:

ρ_e and ρ_a are the densities of exhaust and air respectively (kg/m^3),

V_e is the exhaust velocity (m/s),

U_H is the wind velocity at building height (m/s).

Equation 3.1 reduces to a ratio of velocities (V_e/U_H) because the densities of exhaust and air are nearly equal for non-buoyant tracer studies in the wind tunnel (Stathopoulos *et al.* 2008). In the present study, the syringe sampler can only collect the samples in one minute because of the instrument capabilities (Hajra *et al.* 2010), while the ASHRAE 2007 model considers a 60 minute field averaging time equivalent to two minutes in the wind tunnel. However, studies carried out by Saathoff *et al.* (2009) have also shown that this subtle change in averaging time does not affect the accuracy of near-field tracer dispersion experiments. The samples were drawn using a syringe sampler manufactured by KD Scientific[2], whose suction rate was not varied for all the samples collected from the wind tunnel, irrespective of h_s and M to ensure isokinetic measurements. Tracer gas is released from the rooftop stack and the samples at various receptors are collected by syringes connected by tubes placed underneath the turn-table so that they do not affect the flow of air and tracer gas. The collected samples are injected in a VARIAN 3400 Gas Chromatograph, whose measurement resolution is one and precision approximately 5 %. Additionally, the efficient ventilation system of the laboratory prevents background concentrations affecting the measurements. Additional experimental details can be found in Hajra *et al.* (2011).

3.4 Qualitative analysis

There are very few studies pertaining to the assessment of near-field pollutant dispersion of plumes released from rooftop stacks in the presence of adjacent buildings. Some of these studies were discussed in Chapter 2. For instance, Wilson *et al.* (1998) found that a taller upstream

[2] http://www.kdscientific.com/technical-resources/manuals.asp [Last visit: February 25, 2014].

building caused the plume released from a low building to travel towards the upstream building. Although this was an important finding, quantitative estimates were made only for a few cases. Flow visualisation for a plume released from a low building in the presence of a taller downstream building is shown in Figure 3.2. Pollutants were released at low exhaust speeds (M ~ 1) from a low building placed about 10 m (full-scale) upwind of a tall downstream building.

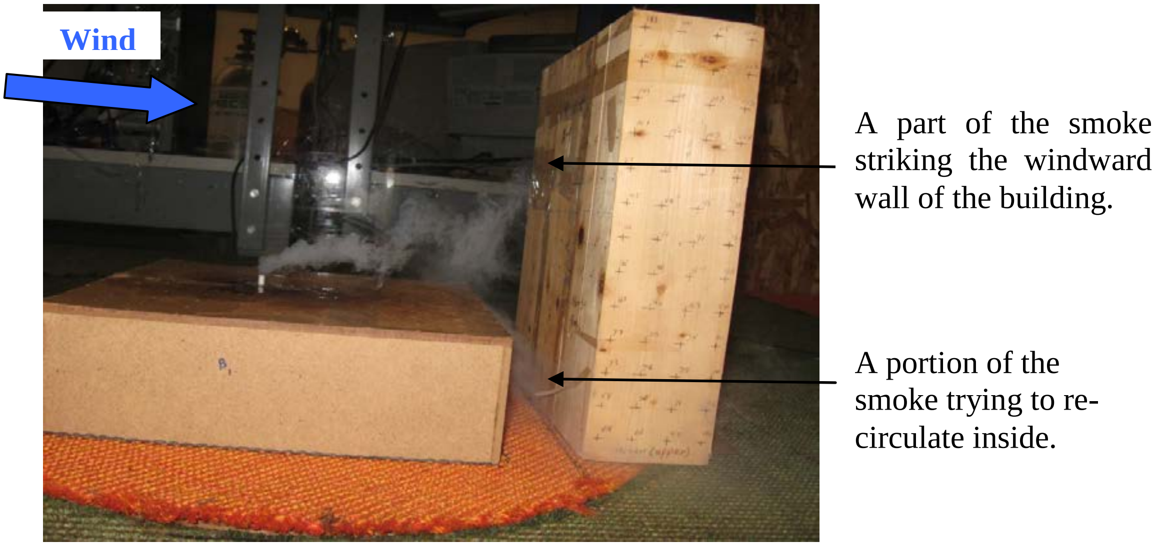


Figure 3.2 – A tall building placed downstream of a low building with source ($\theta = 0^o$).

It was observed that the roof of the emitting building and windward wall of the downstream building were affected. The smoke also had a tendency to re-enter the emitting building through the leeward wall. For further investigation, a tall building was placed upstream and downstream of the low building, which affected the roof of the emitting building and the windward wall of the downstream building.

3.4.1 Identifying key parameters governing plume behaviour

The following was concluded from the flow visualisations:

a) The height and across wind dimension of the adjacent buildings (upstream/downstream) played a major role in altering the plume dispersion.

b) The height of the emitting building, stack location and height, exhaust speed and spacing between buildings, were also critical factors that needed further investigations.

The flow visualisation studies provided a good understanding of the flow characteristics of the plume. Based on these observations various parameters were considered for the wind tunnel study, as presented in Table 3.2.

Table 3.2 – Variables involved in the study and their respective values.

Variable	Range of values	Reasons for adopting such values
M	$1 \le M \le 3$	Previous studies for isolated building have used this range for 'M' (Stathopoulos *et al.* 2004).
Building height	15 – 50 m	Results from field study for a taller upstream building are available.
Spacing	10 – 50 m	Previous studies were conducted on two buildings at Concordia University (Stathopoulos *et al.* 2004).
Width*	30 – 50 m	Flow visualisations showed that a narrow upstream building affected the plume less, when compared to a wider building.
Length	15 – 30 m	Change in length was never considered by any of the previous studies, including ASHRAE models.
X_s	$0 \le X_s \le 20$ m	Previous results for upwind and centrally placed stacks are available (Saathoff *et al.* 2009)
h_s	$1 \le h_s \le 5$ m	Concentrations for an isolated building for stack heights ranging from 1to 5m are available from past studies.
θ	$0 \le \theta \le 45^o$	Most studies focussed on $\theta = 0^o$ with very few studies at $\theta = 45^o$.

* Width refers to the building dimension perpendicular to the wind direction.

Previous studies were only restricted to isolated buildings, as described in Chapter 2. Hence, a comprehensive study involving the changes in various parameters of the adjacent and emitting buildings was found to be necessary.

3.4.2 Parametric study of exhaust dispersion through wind tunnel tests

Table 3.3 presents the dimensions of the six wooden buildings that were used for wind tunnel experiments. The recirculation length of each building was estimated using ASHRAE formulations (see Appendix A). It is also worth noting that the lowest and highest values of recirculation lengths are 22.3 m and 51.2 m respectively. Since the main aim of this project was to assess plume dilution within the zone of recirculation, the spacing between buildings was varied from 10 to 50 m. The various configurations tested in the wind tunnel are presented in Table 3.4. The dimensions mentioned in Tables 3.3 and 3.4 are full-scale dimensions. The receptors were located only along the building centreline and not laterally over the various surfaces. In general, the receptors were located only on the roof, windward and leeward walls of each building and not on the building sidewalls.

Table 3.3 – Dimensions of building models used for wind tunnel experiments.

Building	Height (m)	Width* (m)	Length (m)	Recirculation length (Eq. A1, Appendix A)
B_1	15	50	50	22.3
B_2	30	50	30	35.5
B_3	30	50	15	35.5
B_4	30	30	30	30.0
B_5	54	50	15	51.2
B_6	30	50	50	35.5

* Width refers to the building dimension perpendicular to the wind direction.

Additional details are provided in Hajra *et al.* (2011) and Hajra and Stathopoulos (2012). Figure 3.3 presents a schematic representation of the various configurations, while a complete list of configurations tested in the wind tunnel is also mentioned in Table 3.4. The numbers shown in the figure are the "configuration numbers". The black dots indicate receptor locations on the building surfaces. Although receptors were placed at various locations, only locations where plume concentrations were detected have been shown here.

The stack location from the upwind edge (X_s) was varied from 0 to 20 m and the stack height (h_s) varied from 1 m through 5 m. Exhaust momentum ratios (M) were varied from 1 to 3. This was done so that dilution characteristics for various building surfaces could be thoroughly assessed for different building configurations. Although, the tests were carried out for wind azimuth (θ) of 0^o, 22.5^o and 45^o, $\theta = 0^o$ was found to be the most critical. Hence the results shown in Chapter 4 are only presented for $\theta = 0^o$.

Table 3.4 – Configurations tested in the wind tunnel (total of 18 configurations).

Configuration Number	Configuration	Remarks
1	B_1 (emitting building)	Isolated
2	B_2 upstream of B_1	Taller upstream building
3	B_3 upstream of B_1	Taller upstream building
4	B_4 upstream of B_1	Taller upstream building
5	B_5 upstream of B_1	Taller upstream building
6	B_6 (emitting building)	Isolated
7	B_2 upstream of B_6	Buildings of similar height
8	B_3 upstream of B_6	Buildings of similar height
9	B_4 upstream of B_6	Buildings of similar height
2a	B_2 downstream of B_1	Taller downstream building
3a	B_3 downstream of B_1	Taller downstream building
4a	B_4 downstream of B_1	Taller downstream building
5a	B_5 downstream of B_1	Taller downstream building
7a	B_2 downstream of B_6	Buildings of similar height
8a	B_3 downstream of B_6	Buildings of similar height
9a	B_4 downstream of B_6	Buildings of similar height
10	B_2 upstream and B_5 downstream of B_1	Buildings on either side of emitting building
11	B_2 upstream and B_5 downstream of B_6	Buildings on either side of emitting building

Notes:

i) Across wind dimensions of B_1, B_2, B_3, B_5, and B_6 are equal at 50 m, while for B_4 it is 30 m;

ii) Heights of B_2, B_3, B_4 and B_6 are equal at 30 m, and each of them is twice as high as B_1.

iii) Along wind dimensions of:

B_2 and B_4 are equal at 30 m
B_3 and B_5 are equal at 15 m
B_1 and B_6 are equal at 50 m

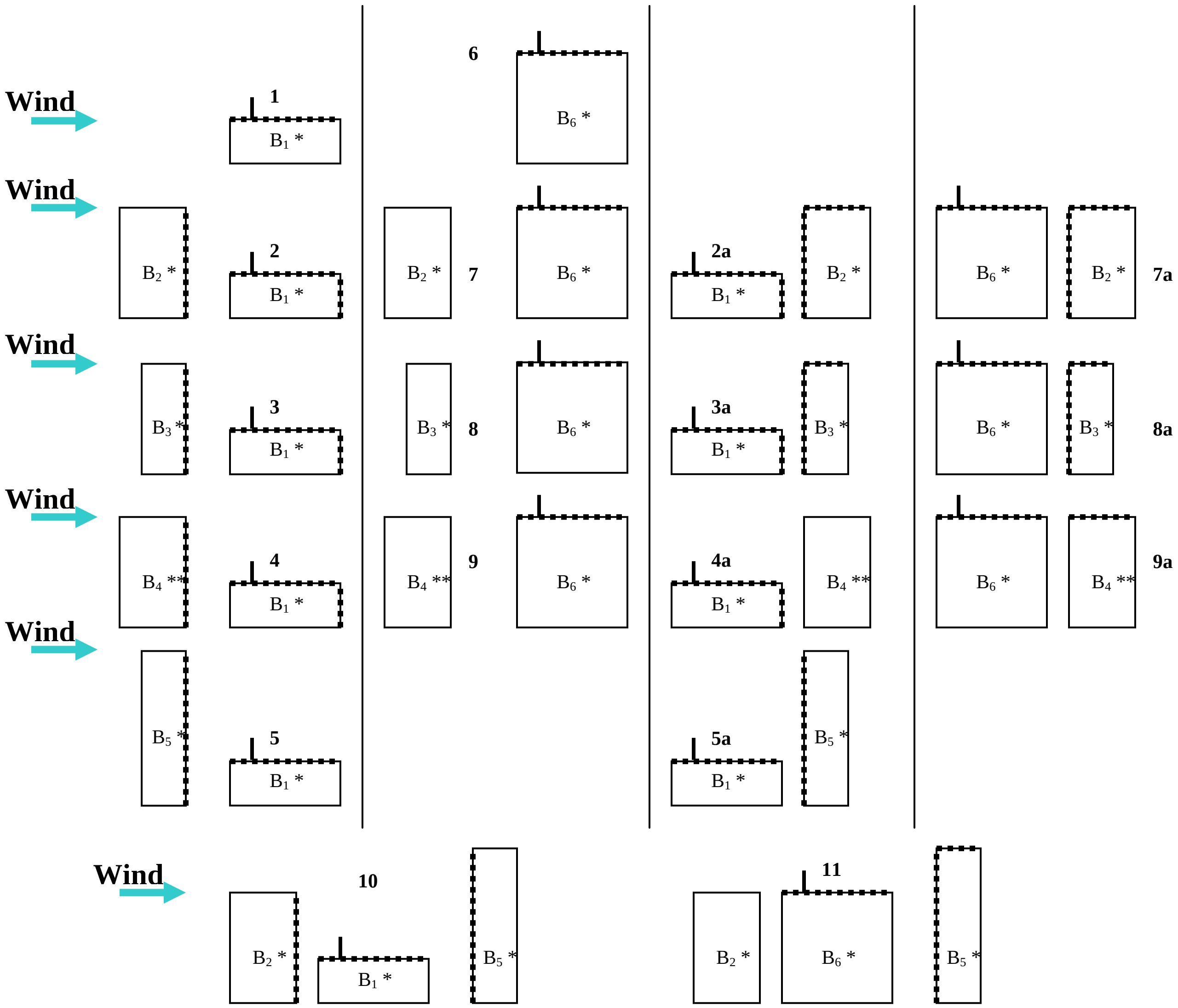


Figure 3.3 – Schematic representation of various configurations tested in the wind tunnel. Only those receptors where concentration of tracer was found have been shown; numbers in bold represent configuration numbers; * and ** represent across wind dimension, where * = 50 m and ** = 30 m.

The experimental results were found to be repeatable within ± 15 % of previously recorded data, which according to Hajra and Stathopoulos (2012) "*is generally considered to be accurate for near-field dispersion studies*".

4. RESULTS AND DISCUSSION

4.1 General

This chapter presents wind tunnel results for different building configurations. These results are compared to the estimates obtained from the ASHRAE 2007 and 2011 models. The results obtained for upstream configurations and downstream configurations are presented in sections 4.2 and 4.3 respectively. Section 4.4 is devoted to configurations involving one building placed upstream and another building placed downstream of the emitting building, while Section 4.5 presents a summary of this chapter. A brief description of the ASHRAE 2007 and 2011 models is presented in Appendix A.

4.2 Upstream building configurations

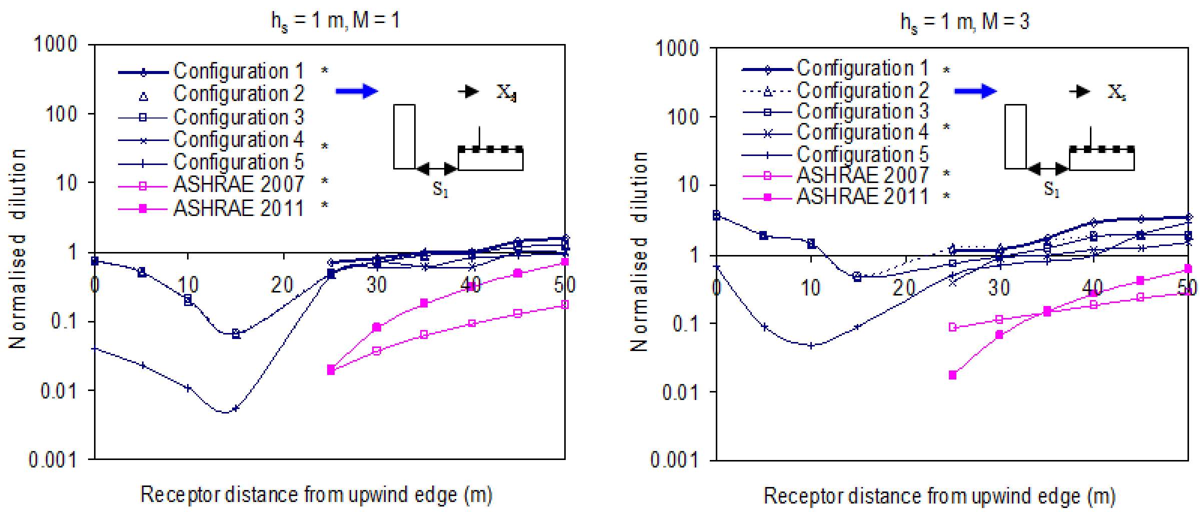
In this section experimental data for different upstream building configurations and results from ASHRAE 2007 and 2011 versions are presented and focuses on dilutions obtained on the roof of the emitting building and the leeward wall of the upstream building, since these surfaces were most affected, especially for taller upstream configurations.

4.2.1 Effect of a taller upstream building

A taller building placed upstream of a low building affects the roof of the emitting building and the leeward wall of the upstream building. The results expressed as normalised dilution on the rooftop of the emitting building are discussed further.

4.2.1.1 Dilution on rooftop of the emitting building (B_1) at X_s = 20 m

Figure 4.1(a) shows rooftop dilution comparisons for Configurations 1 through 5, ASHRAE 2007 and ASHRAE 2011, for h_s = 1 m, M = 1 at X_s = 20 m. It may be mentioned that Configurations 3 and 5 have B_3 and B_5 upstream of B_1 respectively. Also the height of B_5 is nearly twice as much as that of B_3 (see Tables 3.3 and 3.4). A larger recirculation zone is formed in the wake of the upstream building in Configuration 5 when compared to configuration 3, causing greater pollutant concentration on the roof of the emitting building in the former compared to the latter case. However, the dilution become comparable beyond 20 m since the effect of upstream building height gradually reduces downwind of the stack. For upstream buildings of equal height and width, a greater along wind dimension does not affect the recirculation zone formed downwind of it. Hence, comparable dilution for Configurations 2 and 3 are obtained at all points. If the upstream building is longer, flow reattachment is likely to occur but since the heights of the two upstream buildings are equal, the turbulence generated in the wake of the upstream buildings is likely to be of the same magnitude thereby leaving the emitting building very little affected. It is not surprising that no effluent concentrations were found on the rooftop of the emitting building for Configuration 4 within the first 20 m. This is because the upstream building (B_4) has a smaller recirculation length (30 m) and, since the stack is placed sufficiently away from the upwind edge, the plume easily overcomes the recirculation zone of the upstream building, thereby affecting only receptors downwind of stack.



a) b)

Figure 4.1 – Normalised dilution on rooftop of emitting building (B_1) for X_s = 20 m and S_1 = 20 m: a) M = 1; b) M = 3. * Concentrations were only found downwind of the stack.

The ASHRAE 2007 model predicts lower dilutions (about 10 times) than all configurations at M = 1 (Figure 4.1(a)). A similar trend is also observed for M = 3, as shown in Figure 4.1(b). However, ASHRAE 2011 predictions are somewhat better than the 2007 version and predict about 5 times lower dilutions than wind tunnel data of the isolated case, especially closer to the leeward edge of the building at M = 1. At higher exhaust speeds (M = 3), ASHRAE 2011 predictions are lower than wind tunnel data of the isolated building by a factor of 10, although the former does predict more reasonable estimates compared to the 2007 version. ASHRAE 2011 dilutions do not change significantly with increasing M values since the plume spread parameters are functions of turbulence intensities and receptor distance. In general, both ASHRAE models do not predict dilution values upwind of the stack. At h_s > 1 m, Configurations 2, 3 and 5 produce rooftop concentrations at all receptors although the dilution values increase with higher M values. In general, the dilution obtained from all configurations become comparable at receptors downwind of stack, at stack heights greater than 1 m.

4.2.1.2 Dilution on leeward wall of the upstream building (B_2, B_3 and B_4)

Figure 4.2(a) presents normalised dilution on leeward walls of B_2 (Configuration 2), B_3 (Configuration 3) and B_4 (Configuration 4) for h_s = 1 m and M = 1. ASHRAE formulations can only be used to predict rooftop dilution on an emitting building and does not predict dilution on the leeward wall of the upstream building. It may be noted that the upstream building in these configurations is twice the height of the emitting building. Comparable dilution for Configurations 2 and 3 were found at all points on the leeward wall of the upstream building while Configuration 4 resulted in almost 10 times higher dilution than Configurations 2 and 3.

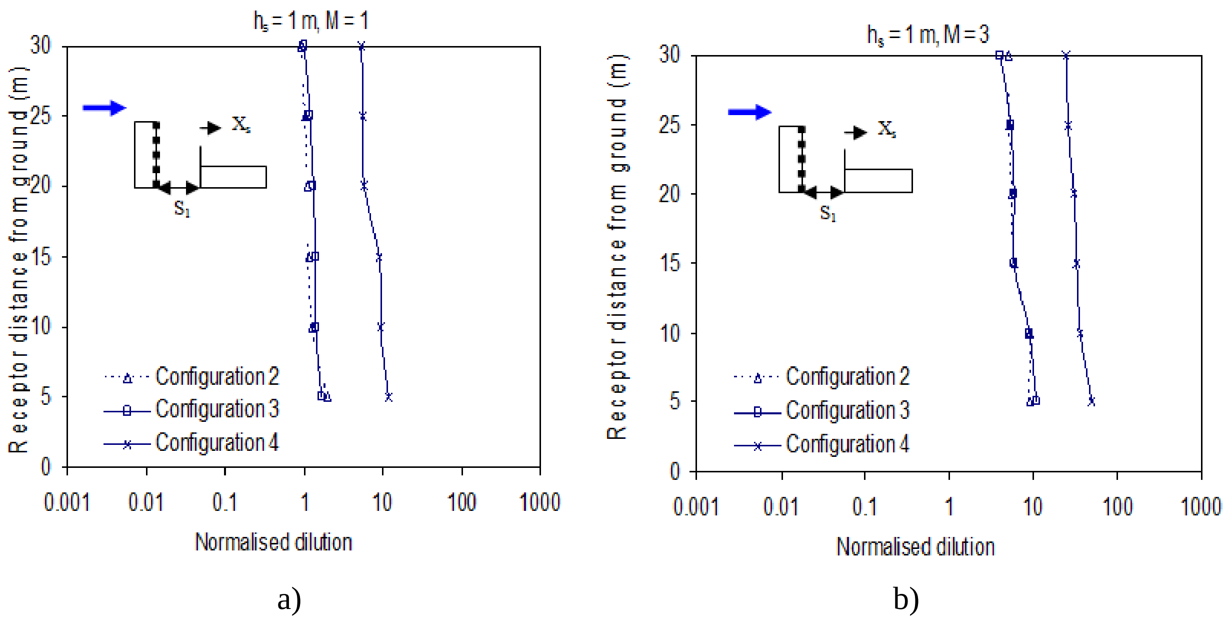


Figure 4.2 – Normalised dilution on leeward wall of upstream building for X_s = 0 and S_1 = 20 m: a) M = 1; b) M = 3.

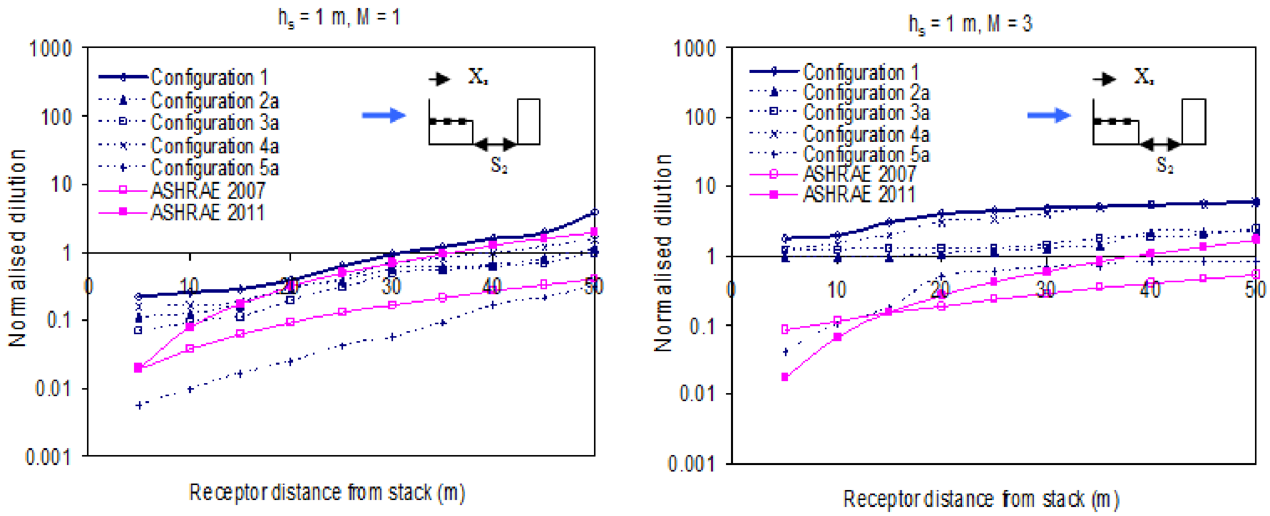
This is due to a reduced across wind dimension of the upstream building in Configuration 4 that creates a smaller recirculation length downwind of the building. A similar trend is also observed for M = 3 as shown in Figure 4.2(b). For greater stack heights (h_s > 1 m), no pollutant concentration was found on the leeward wall of the upstream building, owing to a plume height of more than 3 m above the building surface, resulting in a greater dispersion of the plume. In such case, the plume mostly affects the rooftop of the emitting building thereby leaving the upstream building unaffected. When the stack was placed at 20 m away from the upwind edge of the building, the plume was sufficiently away from the upstream building recirculation zone, making the tracer concentrations so greatly diluted that they were undetectable on the leeward wall of the upstream building. However, a taller upstream building (Configuration 5) of 54 m generated a larger recirculation zone (51.2 m as per ASHRAE) resulting in pollutant concentrations at h_s < 3 m, even for a centrally placed stack; although these trends were similar to Configurations 2 and 3 (see Hajra *et al.* 2011 for additional details).

Dilutions were also found on the leeward wall of the low building with source, for low stacks (h_s = 1 m), since most of the pollutants affected the roof of the emitting building and the leeward wall of the taller upstream building. The results and discussion presented in the preceding section were concerning cases where buildings are placed 20 m apart. In fact, for most cases it was found that the dilution remained unchanged for spacing between 20 and 30 m. However, as the spacing between buildings exceeds this range, the effect of the upstream building gradually reduces as shown in Appendix C. Additional results can be obtained from Hajra *et al.* (2011).

The subsequent section describes the various downstream configurations that were tested in the wind tunnel, including comparisons done with ASHRAE model estimates.

4.3 Downstream building configurations

This section discusses the effect of taller downstream building configurations, with a particular emphasis on the rooftop dilutions on the emitting building, since this surface was more affected. In general, pollutant concentrations were found on the roof and on the leeward wall of the emitting building, as well as on the windward wall and roof of the downstream building. Additional results can also be found in Hajra and Stathopoulos (2012). Figure 4.3(a) shows comparisons of Configurations 1, 2a through 5a, ASHRAE 2007 and ASHRAE 2011 for h_s = 1 m, M = 1, S_2 = 20 m and X_s = 0. It may be noted that although B_2, B_3 and B_4 are twice as tall as B_1, the along wind dimension of B_3 is half of B_2 and across wind dimension of B_4 is 60% of B_2. Comparable dilution was found at all points for Configurations 2a and 3a. This is because a change in along wind dimension of the downstream building does not affect the plume geometry significantly. However, Configuration 4a predicts higher dilution than Configurations 2a and 3a because a narrow building allows a greater portion of the plume to escape through side-leakage leading to higher rooftop dilution on the emitting building, even though these dilutions are somewhat lower than the ones measured for the isolated building case. Configuration 5a predicts about 10 times lower dilution than Configurations 2a and 3a due to the height of the downstream building (B_5), which restricts the plume from dispersing through the air. A similar trend is observed at h_s = 1 m and M = 3, as shown in Figure 4.3(b) although the dilutions for Configurations 4a and 1 become comparable, especially at receptors close to the downwind edge of B_1, because higher exhaust speeds and smaller across wind dimension of the downstream building enhances greater plume spread to reduce the effect of the downstream building. The ASHRAE 2007 predicts very low dilution compared to experimental data at M = 1, leading to overly conservative design. ASHRAE 2011 predictions are comparable to wind tunnel data of the isolated case for M = 1 at receptors beyond 15 m downwind of the stack. However, at M = 3, ASHRAE 2011 predicts about 10 times lower dilutions compared to experimental data of the isolated building, especially closer to the leeward edge of the emitting building, although the estimates are somewhat better than for the 2007 version. In general, the ASHRAE 2011 version was found to be suitable for low M values (M < 3), while the ASHRAE 2007 version was found to be overly conservative for all cases.



a) b)

Figure 4.3 – Normalised dilution on rooftop of B_1 for X_s = 0 and S_2 = 20 m: a) M = 1; b) M = 3.

At greater h_s and M values the dilution predicted by Configurations 2a, 3a and 4a become comparable to the isolated case, particularly closer to the downwind edge.

For higher h_s and M the dilution generated by all configurations were found to be comparable to the isolated case indicating the reduced effects of the downstream building. When the stack is placed at X_s = 20 m, the possibility of plume meandering reduces since the downstream building is of equal height as the source. Hence, comparable dilution for all Configurations was obtained for a given M at h_s > 1 m. Dilutions for low stacks (h_s = 1 m) were also found on the leeward wall of the low building with source, since most of the effluents affected only the roof of the emitting building and windward wall of the downstream building. The results showing the effect of spacing between buildings is presented in Appendix D.

4.4 Buildings upstream and downstream of the emitting building

This section presents the results of one building placed upstream and one building placed downstream of an emitting building. More specifically, results obtained with a taller building placed upstream and another taller building placed downstream of an emitting building (Configuration 10) are presented, with additional results in Appendix E.

Figure 4.4(a) shows normalised dilution on the rooftop of B_1 for h_s = 1 m, M = 1 and X_s = 0 for Configurations 1, 10, ASHRAE 2007 and ASHRAE 2011. Results show that the dilutions predicted by Configuration 10 are almost 20 times lower than those predicted by Configuration 1 (isolated case). This is because the plume gets trapped in between two buildings (plume meandering). Also, the recirculation zone of the taller upstream building brings the plume closer to the leeward wall of the upstream building and the rooftop of the emitting building. A similar trend is observed at h_s = 1 m and M = 3 as shown in Figure 4.4(b) although the dilution is somewhat higher than those produced at M = 1 due to higher exhaust speeds. This trend remains unchanged for higher h_s = 3 m. At h_s = 5 m and M = 3, the dilutions obtained from Configuration 10 and the isolated case become comparable, possibly because the plume rise is sufficient to overcome the effect of adjacent buildings. ASHRAE 2007 values are found to be lower than wind tunnel data of the isolated building, while the 2011 version data compare well with wind tunnel findings, but only at M = 1. In general, both ASHRAE versions are incapable of simulating adjacent building effects due to reasons explained previously.

Centrally placed stacks generate a plume trajectory that is similar to taller upstream configurations discussed previously. In fact, the trends of dilutions found on the leeward wall of the upstream building (B_2) are similar to those found in upstream building configurations (Figure 2.2).

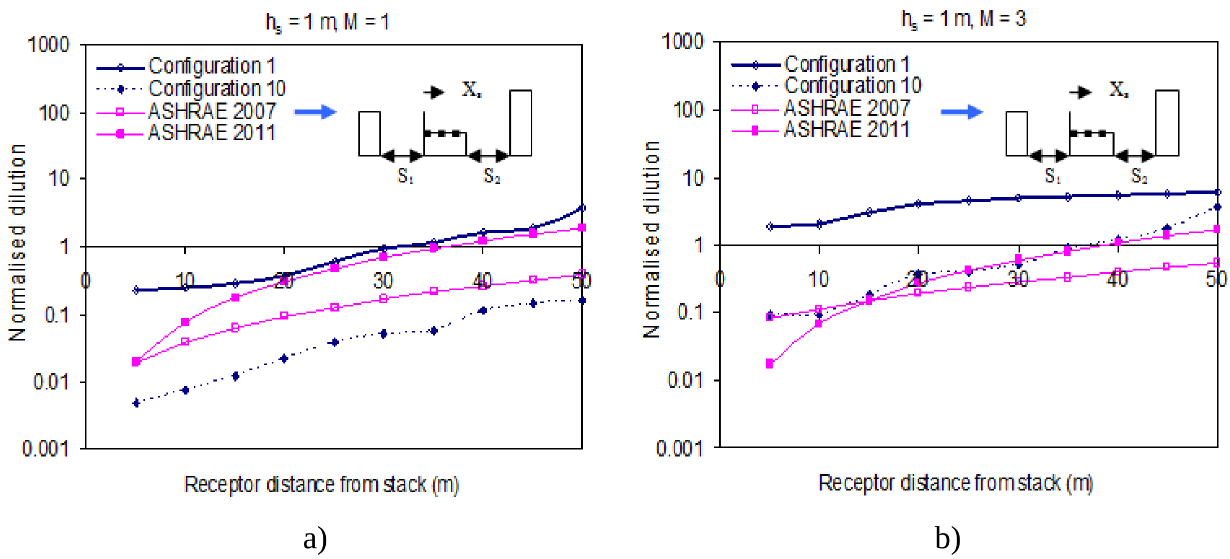


Figure 4.4 – Normalised dilution on rooftop of B_1 for X_s = 0 and S_1 = S_2 = 20 m: a) M = 1; b) M = 3.

4.5 Summary

This chapter primarily focussed on four cases namely:

a) One isolated building (source);

b) Buildings of different geometries placed upstream of the source;

c) Buildings of different geometries placed downstream of the source;

d) One building placed upstream and another building placed downstream of the source.

Wind tunnel data obtained from the tracer gas study for different configurations were compared to the ASHRAE model data. It was found that when the buildings were placed within the recirculation zone of the emitting building, taller upstream buildings caused the plume to travel towards the leeward wall of the upstream building thereby increasing plume concentrations on the leeward wall of the upstream building and on the rooftop of the emitting building. A taller downstream building disallowed the plume from escaping and increased rooftop concentrations on the emitting building. Buildings placed on either side of the source reduced plume dilution on the emitting building roof due to increased plume meandering. As the spacing between buildings increased the plume geometry gradually shifts towards the isolated building. ASHRAE 2007 predictions are overly conservative, while the 2011 predictions are reasonable, especially at low M values. Both ASHRAE models can only be used to estimate plume dilution on the rooftop of isolated buildings and cannot be used to estimate dilutions on adjacent building surfaces.

5. UTILISATION OF RESEARCH RESULTS TO IMPROVE THE ASHRAE MODEL

5.1 Introduction

In this chapter, the wind tunnel results of the current study are used to improve ASHRAE 2007 estimates. In this context, the pollutant dilution on adjacent building surfaces is expressed in terms of the roof dilution on the isolated building, followed by rectifying the ASHRAE 2007 model. Section 5.2 presents comparisons for wind tunnel data and ASHRAE models for an isolated building. Section 5.3 describes the grouping of different building configurations, based on the dilution results discussed in Chapter 4. Comparisons of dilution for different adjacent building configurations and the isolated case are presented in section 5.4, followed by the proposed rectification of the ASHRAE models in section 5.5. Application of the rectified ASHRAE 2007 model for the given problem is presented in section 5.6, followed by a summary of this chapter in section 5.7.

5.2 Comparisons of ASHRAE and Wind tunnel data

Figure 5.1 shows comparisons for wind tunnel data for Configuration 1 (isolated building), ASHRAE 2007 and 2011 results for h_s = 1 m, M = 3 and stack location (X_s) at the upwind edge, in terms of normalised dilution. Results show that wind tunnel dilutions on the leeward edge are somewhat higher than those found close to the stack due to a greater dispersion of the plume.

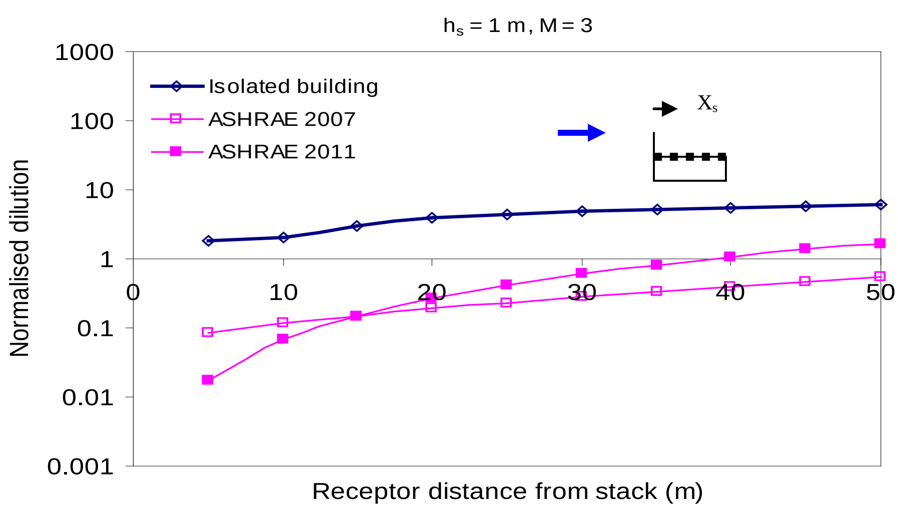


Figure 5.1 – Normalised dilution on rooftop of isolated building for h_s = 1 m and M = 3.

The ASHRAE 2007 model predicts almost 10 times lower dilutions than wind tunnel data at all receptors because the formulations do not take into account the turbulence generated around the building and the local topography. Additionally, the ASHRAE 2007 model predicts low plume rise, making the dilution estimates overly conservative. ASHRAE 2011 predictions are about a factor of 5 lower than wind tunnel data close to the leeward edge of the building. ASHRAE 2011 predictions are somewhat better than the 2007 version, although the former predicts somewhat lower dilutions than the latter very close to the stack due to low plume rise estimates.

5.3 Grouping of different building configurations

In Chapter 4, a total of 18 different building configurations were tested in the wind tunnel; these included: 2 isolated cases (source), 7 upstream building configurations, 7 downstream configurations and 2 adjacent building configurations involving one building placed upstream and one building placed downstream of the source.

Considering the plume structure of the isolated case and comparing it to adjacent building configurations (Figure 3.3), it is generally observed that:

a. Upstream Configurations 2 and 3 generate comparable dilution on all building surfaces (Figure 4.1). A similar trend is also observed for downstream Configurations 2a and 3a as shown in Figure 4.3.

b. Configuration 4 generates comparable roof dilution on emitting building with the isolated case (Figure 4.1). Similarly, Configurations 1 and 4a produce comparable dilution on rooftop of emitting building.

c. A building of lower than or equal height with the emitting building, placed upstream (or downstream) of the emitting building does not influence the plume geometry significantly.

d. Configuration 10 which consists of a tall building on either side of the emitting building can be expressed as a combination of Configurations 2 and 5a based on the results presented in Chapter 4 (section 4.4). Similarly, Configuration 11 may be expressed as a combination of Configuration 6 and Configuration 3a.

This allows one to reduce and simplify the 18 configurations described in Figure 3.3 to only 6, as shown in Figure 5.2.

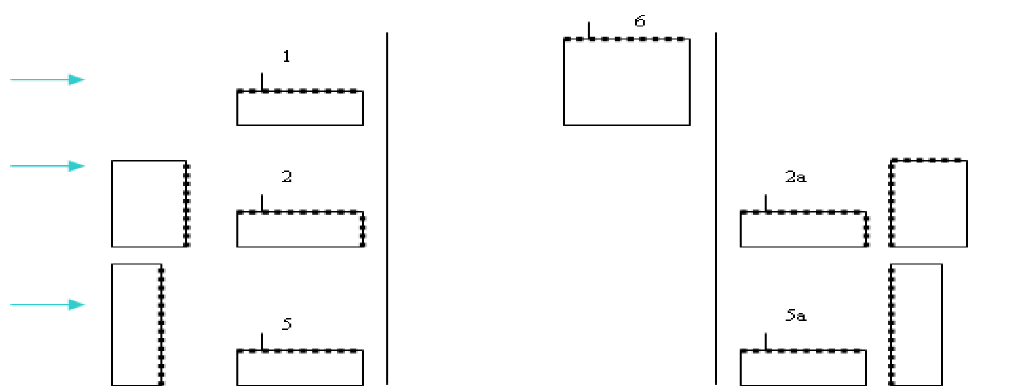


Figure 5.2 – Reduced set of building configurations based on the plume characteristics for various proximity cases.

5.4 Comparisons of adjacent building configurations with the isolated case

This section compares wind tunnel dilution estimates obtained for different adjacent building configurations and the isolated case. The building surfaces include the roof of the emitting and downstream buildings as well as the wall of adjacent buildings. Estimation of factors for each building surface will be discussed separately in the following sub-sections.

5.4.1 Roof dilution on emitting building

The factors have been estimated separately for roof dilution on emitting building for “a taller upstream building” and “a taller downstream building” (Hajra, 2012). Configurations 2, 3 and 5 (Figure 3.3) have been considered to assess plume dilution on roof of emitting building with respect to the isolated case (Configuration 1). In order to assess and compare the dilution between various configurations, the ratio of the dilution on roof of isolated building to dilution on roof of emitting building for adjacent building configurations is introduced:

$$f1 = \frac{D_i}{D_a} \tag{5.1}$$

where

D_i is the dilution on roof of the isolated building,

D_a is the dilution on roof of the emitting building for adjacent building configurations.

For stack located at the upwind edge ($X_s = 0$) comparisons between the average dilution of Configurations 2 and 3 and the isolated case (Configuration 1) are presented in Figure 5.3. The receptor distance from the upwind edge (x) has been expressed in terms of the along wind dimension (L) of the emitting building. An average dilution for Configurations 2 and 3 was estimated since the rooftop dilutions from both these configurations were comparable (see Figure 4.1). An average factor (f1) was estimated by dividing the dilution obtained for the isolated case by the average dilution of Configurations 2 and 3 at each receptor, as described by equation 5.1. This was done so that a relationship for a taller upstream building twice as high as the emitting building and an isolated building could be established. It may be mentioned that the buildings in this case are spaced 0.4L apart.

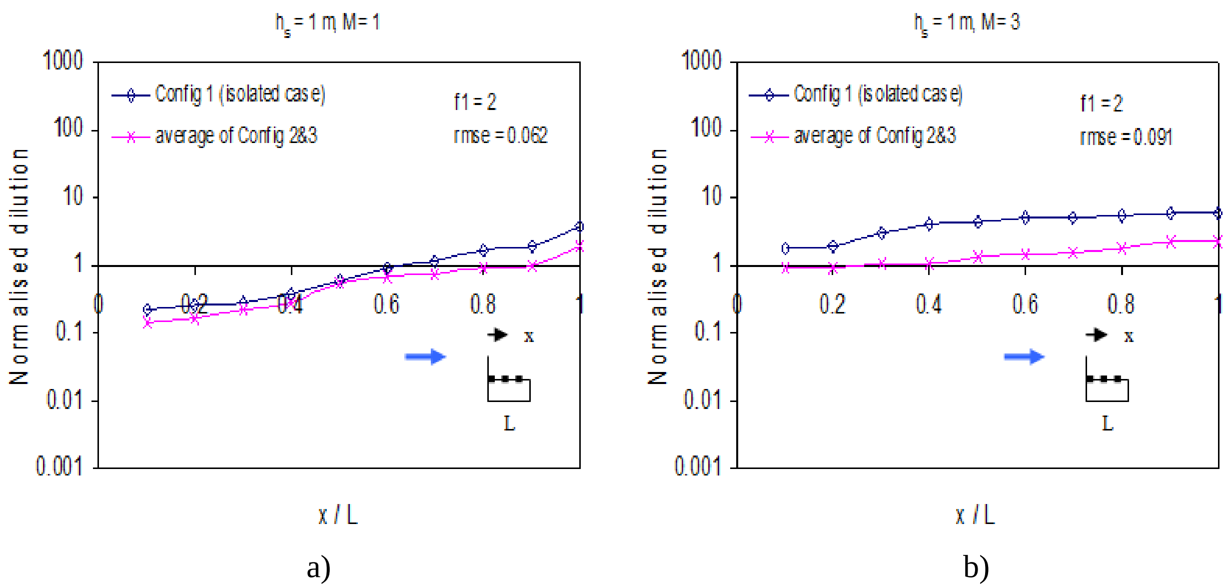


Figure 5.3 – Normalised dilution on rooftop of the emitting building for: a) M = 1; b) M = 3.

It may be recalled from Chapter 4 that for upstream configurations within 0.6L and downstream configurations within 0.5L, a change in spacing does not alter the plume geometry significantly. The factor f1 shown in Figure 5.3 was found by minimising the root mean square error (rmse), which is defined as:

$$rmse = \frac{1}{n}\sqrt{\sum(1-\frac{p_i}{m_i})^2} \tag{5.2}$$

where:

n represents the total number of receptor locations,

p_i and m_i are the predicted and measured normalised dilutions respectively, at receptor i.

In the current case, the measured dilution (m_i) is wind tunnel data of Configuration 1 and predicted dilution (p_i) is the factored dilution. For instance, in Figure 5.3(a), f1 = 2 was determined by dividing the dilution estimated on the roof of the isolated building (Configuration 1) by the average dilutions of Configurations 2 and 3 at each receptor and by minimising the rmse which was found to be 0.062.

A similar approach was also adopted to estimate factors for downstream configurations. The following sub-section describes the estimation of factors for the roof of the downstream building, using the dilution value on the downwind edge of the emitting building.

5.4.2 Roof dilution on downstream building

In this section the relationship between the roof dilution on the downstream building and the roof dilution on the downwind edge of the emitting building is examined. The ratio of the dilution on roof of downstream building to dilution on downwind edge of emitting building is introduced and defined as:

$$f2 = \frac{D_d}{D_{de}} \tag{5.3}$$

where

D_d is the dilution on the roof of the downstream building,

D_{de} is the dilution on downwind edge of the emitting building.

It may be recalled, from the results of Chapter 4, that dilution on the roof of the downstream building was found only when the downstream building is of equal height or about twice as tall as the emitting building. Buildings more than twice the height of the emitting building disallow the plume to accumulate on the roof of the downstream building due to their greater height. It is understandable that the dilution on the downwind edge of the emitting building may be closely related to the roof dilution of the downstream building since this is the closest surface of the emitting building from the downstream building. Similarly, factors were estimated to relate the dilution on the wall of any building to the roof dilutions on the emitting building, as discussed further.

5.4.3 Wall dilution on both buildings

Wall dilution consists of dilution on leeward wall of the upstream building and windward wall of the downstream building as well as dilution on the leeward wall of the low building. It is reasonable to relate the dilution downwind of the stack and the dilution obtained on the leeward wall of the upstream building since these building surfaces are close to each other. Therefore, a factor f3 may be defined as:

$$f3 = \frac{D_s}{D_{lu}} \tag{5.4}$$

where

D_s is the dilution downwind of stack,

D_{lu} is the dilution on leeward wall of the upstream building.

Since dilutions were found on the leeward wall of the emitting building for both upstream and downstream building configurations, the ratio of the dilution on downwind edge of emitting building to the dilution on leeward wall of emitting building is defined as:

$$f4 = \frac{D_{de}}{D_{le}} \tag{5.5}$$

where

D_{de} is the dilution on the downwind edge of the emitting building,

D_{le} is the dilution on the leeward wall of the emitting building.

Similarly, the dilution on the windward wall of the downstream building may be found by relating it to the dilution on the downwind edge of the emitting building since these building surfaces are close to each other. Hence, a factor f5 can be defined:

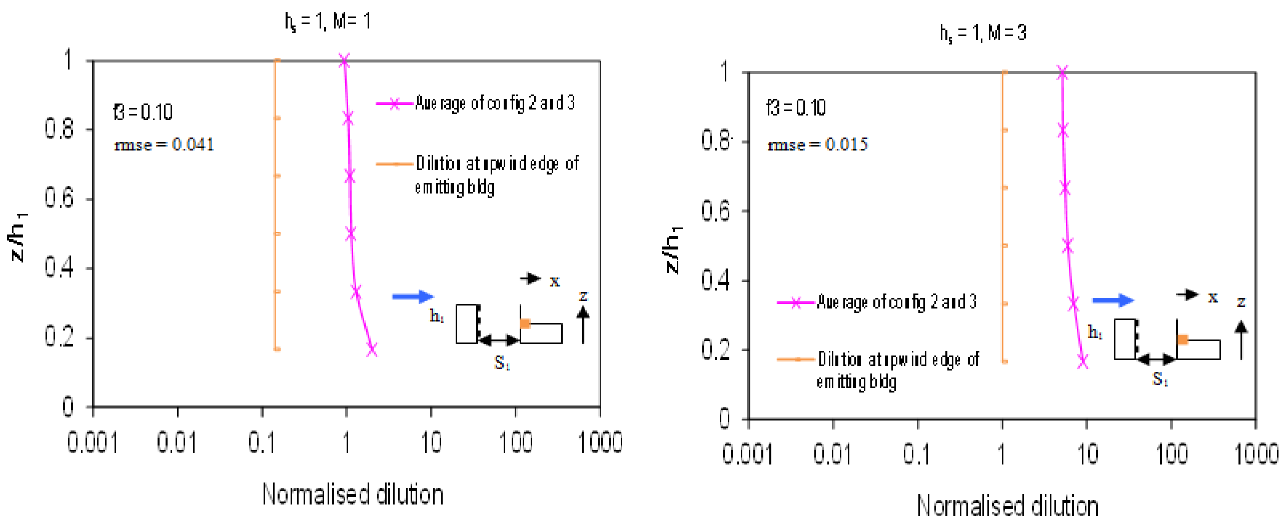
$$f5 = \frac{D_{de}}{D_{wd}} \tag{5.6}$$

where

D_{de} is the dilution on downwind edge of the emitting building,

D_{wd} is the dilution on windward wall of the downstream building.

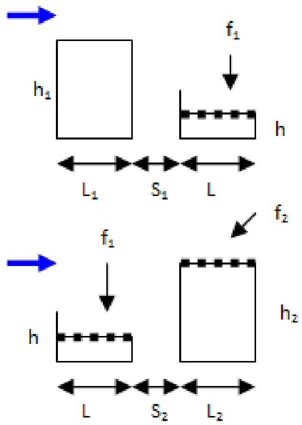
Figure 5.4 shows comparisons for the average normalised dilution for Configurations 2 and 3 and the dilution at the upwind edge of the emitting building. The factors (f3) shown in Figure 5.4 are average factors. Tables 5.1 and 5.2 summarise the findings of this section.



a) b)

Figure 5.4 – Normalised dilution on leeward wall of upstream building: a) M = 1; b) M = 3.

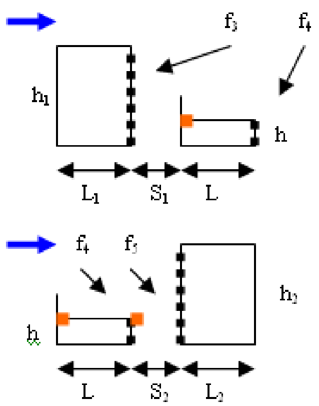
Table 5.1 – Roof dilution on a building surface as a function of the emitting building.



Configuration	X_s	h_s	M	Value of factor (rmse)
$h_1/h = 2$	0	1,2,3	1,2,3	f1 = 2 (0.033-0.091)
$h_1/h = 2$ or 4	0.4L	1,3	1,3	f1 = 1.0 (0.024-0.082)*
$h_2/h = 2$	0	1,2,3	1,2,3	f1 = 2.0 (0.018-0.033)
$h_2/h = 4$	0	1,2,3,	1,2,3	f1 = 12 (0.046-0.065)
$h_2/h = 2$	0 or 0.4L	1, 3	1,2,3	f2 = 2.8 (0.016-0.020)
$h_2/h = 1$	0 or 0.4L	1, 3	1,2,3	f2 = 1.12 (0.011-0.036)

Notes
* dilution obtained only downwind of stack.
f1 = (dilution on roof of isolated building)/(dilution on roof of emitting bldg. for adjacent bldg. config.)
f2 = (dilution on roof of downstream building)/(dilution on downwind edge of emitting building)

Table 5.2 – Wall dilution on a building surface as a function of the emitting building.



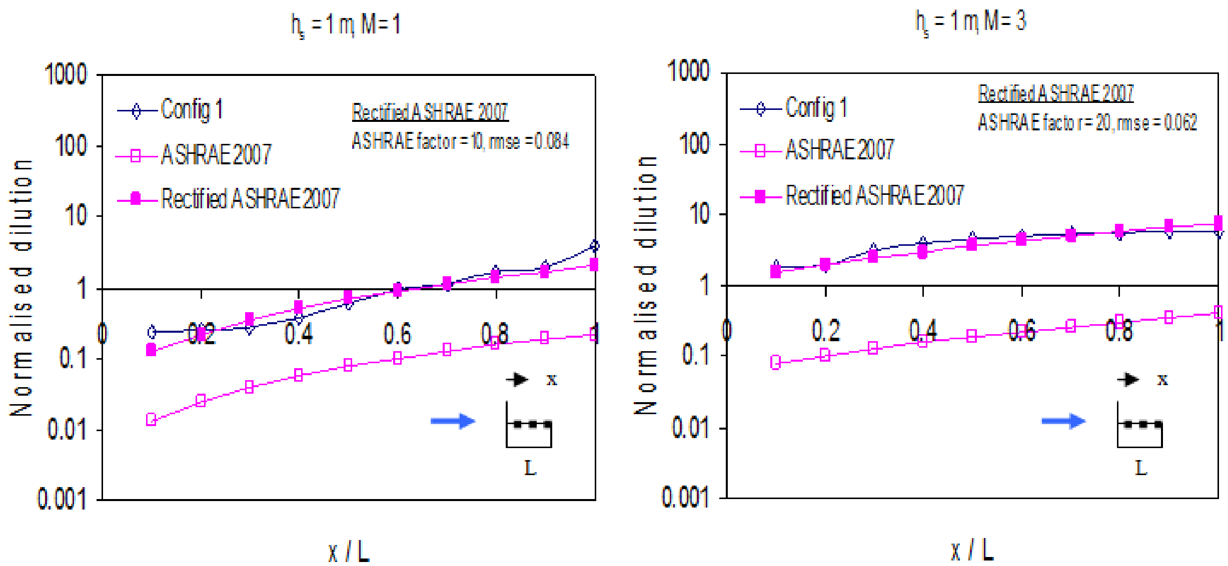
Configuration	X_s	h_s	M	Value of factor (rmse)
$h_1/h = 2$	0	1,3	1, 3	f3 = 0.10 (0.041-0.055)
$h_1/h = 4$	0	1,3	1,3	f3 = 0.3 (0.0431-0.0891)
$h_1/h = 4$	0.4L	1	1,3	f3 = 0.15 (0.0581)
$h_1/h = 4$	0.4L	3	1,3	f3 = 0.25 (0.073)
$h_1/h = h_2/h = 2$	0	1	1,2	f4 = 1 (0.016-0.066)
$h_2/h = 2$ or 4	0,0.4L	1,3	1,3	f5 = 0.40 (0.041-0.085)

Notes
f3 = (dilution downwind of stack)/(dilution on leeward wall of upstream bldg.)
f4 = (dilution on downwind edge of emitting bldg.)/(dilution on leeward wall of emitting building)
f5 = (dilution on downwind edge of emitting bldg.)/(dilution on windward wall of downstream bldg.)

The tables in this section were primarily prepared to relate the dilution on the roof/wall of the emitting and adjacent building surfaces in terms of the isolated case. The next step is to rectify the ASHRAE 2007 model for the isolated case, as discussed further.

5.5 Rectification of the ASHRAE 2007 model

This section presents the factors that were evaluated by comparing ASHRAE 2007 model with experimental data for the isolated building. These factors, combined with those described in Tables 5.1 and 5.2, can be used to estimate plume dilution on various building surfaces. The ASHRAE models were applied to the two isolated buildings - low-rise (15 m) and intermediate (30 m) - that were tested in the wind tunnel and a factor was obtained for each model. For instance, Figure 5.5 shows comparisons for wind tunnel data, ASHRAE 2007 model data and their respective rectified values for h_s = 1 m and X_s = 0.



a) b)

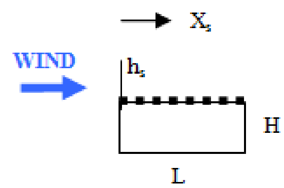
Figure 5.5 – Normalised dilution on rooftop of the low rise building: a) M = 1; b) M = 3.

An average factor for each model was obtained by dividing the wind tunnel data by the respective ASHRAE model values and minimising the rmse. A rectified model was then obtained by multiplying that factor by the corresponding ASHRAE value. As shown in Figure 5.5(a), a factor of 10 was obtained for rectifying the ASHRAE 2007 model and, at M = 3, a factor of 20 was used to rectify the ASHRAE 2007 model (Figure 5.5(b)). Similarly, factors were also determined for higher h_s and M values, as well as for centrally placed stacks (X_s = 0.4L) for the low building (15 m high) and intermediate building (30 m).

It is normal to expect low correlation between experimental data and model estimates (higher root mean square errors) in such micro-scale modelling problems. For instance, Stern and Yamartino (2001) had correlations ranging from 0.637 - 0.888 and root mean square error from 0.041 - 1.341, for micro scale dispersion model within a street canyon to estimate concentrations due to traffic flow. From the results, it was observed that the ASHRAE 2007 estimates are more conservative than the 2011 estimates, and hence, the present chapter is devoted to rectifying the 2007 approach (Table 5.3). Factors obtained from Tables 5.1, 5.2 and 5.3 are applied to present and previous studies to rectify ASHRAE 2007 estimates, as discussed further.

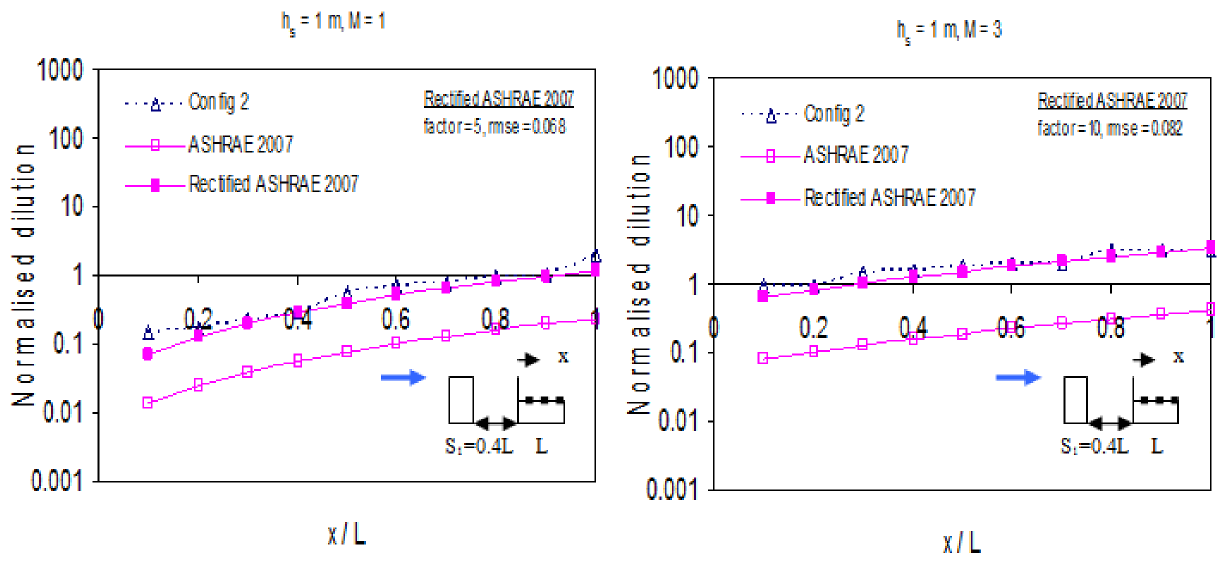
Table 5.3 – Factors to rectify ASHRAE 2007 for the isolated building.

X_s	h_s	M	ASHRAE 2007	
			ASHRAE factor (low-rise building – 15 m)	ASHRAE factor (intermediate building – 30 m)
0	1,3,5	1	10 (0.084-0.092)	10 (0.085-0.099)
0	1,3	2	15 (0.088-0.091)	10 (0.081-0.085)
0	1,3,5	3	20 (0.044-0.083)	10 (0.072-0.094)
0.4L	1	1,2,3	10 (0.081-0.098)	10 (0.091-0.098)
0.4L	3	1,2,3	10 (0.094-0.099)	20 (0.092-0.099)
0.4L	5	1	10 (0.051)	10 (0.096)
0.4L	5	3	10 (0.093)	20 (0.095)



5.6 Application of the rectified ASHRAE 2007 model to the present study

This approach was applied to a taller upstream building twice as high as the low building (Configuration 2) for h_s = 1 m and X_s = 0 as shown in Figure 5.6. In this case the ASHRAE 2007 values were obtained for the isolated case (identical values from Figure 5.5) and multiplied by the appropriate factor. The factor was determined from Tables 5.1 and 5.3. For instance, from Table 5.1 for h_1/h = 2, X_s = 0, h_s = 1 m and M = 1, f1 = 2 can be obtained. It may be recalled that this factor was obtained by dividing the roof dilution for the isolated case and upstream building configuration. For X_s = 0, h_s = 1 m, M = 1, Table 5.3 gives the ASHRAE factor of 10, which is the ratio of wind tunnel dilution for the isolated case and the ASHRAE 2007 values. Therefore, in order to relate ASHRAE 2007 values to the wind tunnel dilution of Configuration 2, a factor of 5 is obtained by dividing 10 by 2, as shown in Figure 5.6(a). The rectified ASHRAE 2007 results compare well with experiment at all receptors. Figure 5.7 presents a sketch showing the calculations for Figure 5.6(a).



a) b)

Figure 5.6 – Normalised dilution on rooftop of low building: a) M = 1; b) M = 3.

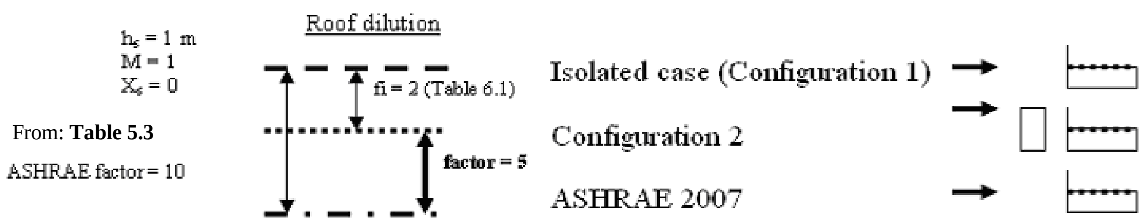


Figure 5.7 – Sketch showing the calculation of the factor used to generate the data shown in Figure 5.6(a).

Figure 5.8 shows dilution on the leeward wall of the upstream building of Configuration 2 for h_s = 1 m, X_s = 0 and S_1 = 0.4L. It may be mentioned that the factors may be applied for adjacent building configurations within spacing of 0.6L for upstream building configurations and 0.5L for downstream configurations. Beyond 0.6L the dilution on emitting building may be estimated by using the factors for the isolated case (Table 5.3). The dilution on the leeward wall of the upstream building is estimated from the roof dilution obtained on the receptor immediately downwind of stack. For instance, from Figure 5.6(a) for h_s = 1 m and M = 1, the rectified ASHRAE 2007 dilution at 0.1L is 0.095. From Table 5.2, f3 = 0.1 is obtained for h_1/h = 2. It may be recalled that f3 represents the ratio of roof dilution downwind of stack to the dilution on leeward wall of upstream building. Therefore, 0.095 divided by 0.1 gives about 0.95 as the factored dilution from the rectified ASHRAE 2007 model (Figure 5.8(a)).

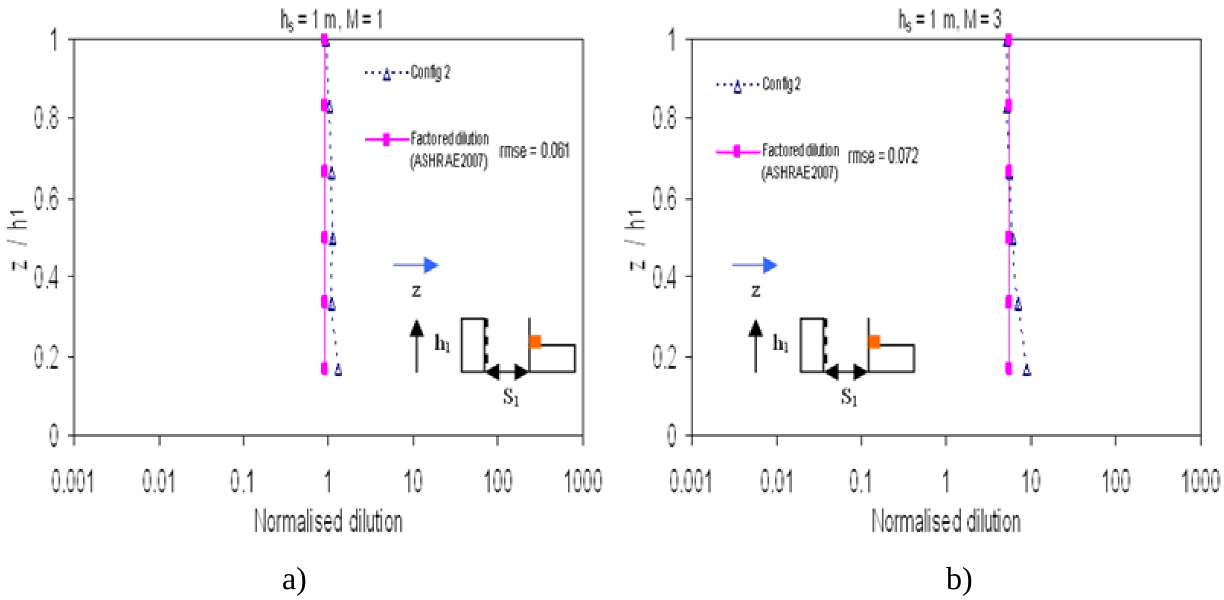


Figure 5.8 – Normalised dilution on leeward wall of upstream building: a) M = 1; b) M = 3.

5.7 Summary

This chapter presented methods to modify the ASHRAE 2007 model. The rectified ASHRAE method to determine pollutant dilution on various building surfaces consists of a two-step process:

a) Establishing a relationship between dilution estimates from adjacent building configurations and the isolated case (Tables 5.1 and 5.2).

b) Comparing ASHRAE 2007 dilution values for isolated case and wind tunnel data from the present study (Table 5.3).

The rectified ASHRAE 2007 approach compared well with results from the present study (e.g. Figure 5.6). Additional validations of the rectified ASHRAE 2007 approach by using the experimental data from Wilson *et al.* (1998) and Stathopoulos *et al.* (2004) are provided in Appendix F.

The subsequent chapter presents design guidelines for safe placement of stack and intake on various building surfaces, based on this study.

6. DESIGN GUIDELINES FOR SAFE PLACEMENT OF STACK AND INTAKE ON BUILDING SURFACES

6.1 General

This study examined the near-field pollutant dispersion characteristics of rooftop emissions in the presence of adjacent buildings through tracer gas studies in a wind tunnel. ASHRAE 2007 dilution estimates were found to be overly conservative for all cases, while ASHRAE 2011 predictions were found to be reasonable for some cases. Efforts were also made to rectify the ASHRAE 2007 estimates for the isolated building and extend their application to adjacent building surfaces. Based on the experimental results, design guidelines for safe placement of stack and intake on various building surfaces are described in this Chapter.

6.2 Design guidelines for placement of intake and stack

This section presents some guidelines for engineers regarding the safe placement of stack and intake on a building. The suitability of the location of stacks and intakes on a building surface will depend on a number of factors such as the local topography, the turbulence and the material being released from the stack. The guidelines have been presented separately for each building configuration, and are summarised in Figure 6.1.

6.2.1 Upstream building configurations

Building configurations tested in the wind tunnel include taller upstream building configurations and an upstream building of similar height as the emitting building.

<u>Taller upstream building</u>

1. When the spacing between the buildings exceeds the recirculation length of the upstream building, intakes may be placed on both the leeward wall of the upstream building and close to the downwind edge of the emitting building, for a given stack height and M value.

2. When the emitting building lies within the recirculation zone of the upstream building, intakes should not be located upwind of the stack; they may be placed closer to the leeward wall of the emitting building.

<u>Upstream building of lower or similar height with the emitting building</u>

1. When an upstream building of lower or similar height is placed at a distance which is greater than the recirculation length of the upstream building, irrespective of stack location and height, intakes may be placed on the roof of the upstream building.

2. When a building is located within the recirculation zone of the upstream building, for a given stack location, intakes may be placed on the leeward wall of the emitting building and close to the windward wall of the upstream building.

6.2.2 Downstream building configurations

Design guidelines for the placement of intake and stack are discussed for downstream building configurations of taller or similar height as the emitting building since the plume structure does not change significantly.

Taller or similar height downstream building

1. When a downstream building is placed within the recirculation length of the emitting building, intakes should not be located close to the leeward wall of the emitting building.

2. When spacing between buildings exceeds the recirculation length of the emitting building, intakes may be placed on either building surface.

3. For any value of h_s, M and spacing, intakes must be avoided immediately downwind of a low stack with low exhaust speeds (say h_s = 1 m and M = 1) due to increased plume downwash effects, although it is safer to place them upwind of stack.

6.2.3 Buildings placed upstream and downstream of the emitting building

A configuration where a building is placed upstream and another building is placed downstream of the emitting building, affects the leeward wall of the upstream building, the roof of the emitting building as well as the windward wall and roof of the downstream building. As presented in Figure 3.3, Configuration 10 consisted of a low building (B_1) with a taller upstream building (B_2) and a taller downstream building (B_5), while Configuration 11 consisted of an upstream building (B_2) of the same height as the emitting building (B_6) and a taller building (B_5) downstream of the emitting building (B_6).

For these configurations, the following guidelines may be adopted (Figure 6.1 presents a schematic summary of the design guidelines for safe placement of intakes):

1. For Configuration 10, if spacing between the buildings is within the recirculation length of the taller upstream building, intakes must be avoided upwind of stack for any h_s and M; it may be safer to place them closer to the leeward wall of the downstream building.

2. For Configuration 11, intakes may be placed on building surfaces upwind of stack and closer to the leeward wall of the taller downstream building for any given h_s, M and spacing between buildings.

3. In general, the guidelines for a taller upstream building and a taller downstream building configuration may be adopted for Configuration 10.

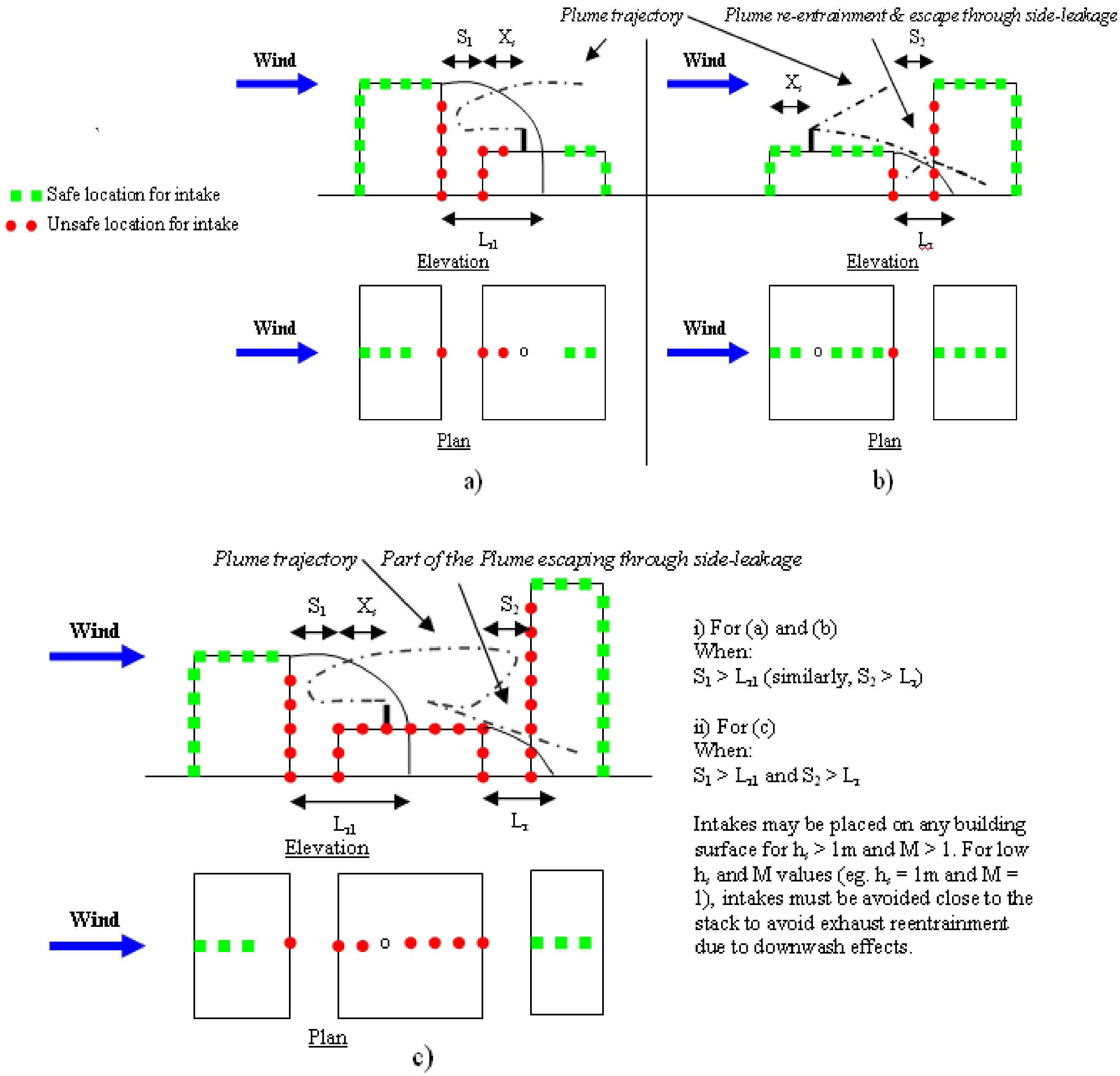


Figure 6.1 – Schematic representation for suitability of intake locations: a) Upstream configurations; b) Downstream configurations; c) Buildings placed upstream and downstream of an emitting building.

7. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

7.1 Summary

This report focussed on a detailed wind tunnel study of near-field pollutant dispersion for different adjacent building configurations. In this context, pollutant concentrations were measured at various building surfaces and the effect of various parameters such as h_s, M, spacing between buildings, X_s and geometries of adjacent and emitting buildings were studied. Comparisons with ASHRAE models showed that the models were less suitable when applied to adjacent building configurations. This was followed by suggestions to rectify the ASHRAE 2007 model to obtain reasonable dilution estimates on various building surfaces. Design guidelines for the safe placement of stack and intake were also suggested based on the results of this study.

The study is a direct contribution to the objectives of IRSST in terms of enhancing the occupational health and safety in the work environment. Indeed a better placement of inlets relative to outlets of laboratory, hospital and other industrial buildings is expected to minimize the risk of reingestion of toxic fumes and other pollutants released from rooftop stacks and avoid the deterioration of indoor air quality. The results of the study will contribute to the improvement of building design standards and regulations and thereby will enhance the safety and the well-being of workers in buildings.

7.2 Conclusions

The conclusions that can be drawn from this study have been divided into three subsections, as follows:

7.2.1 Wind tunnel study

1. The results of this study suggest that when the emitting building lies within the recirculation length of a taller upstream building, a change in along wind dimension of the adjacent building has a negligible effect on the plume dilutions on the various building surfaces.

2. A taller downstream building placed within the recirculation length of the emitting building (L_r) causes the plume to be engulfed within L_r, thereby affecting the leeward wall of the emitting building and the windward wall of the downstream building.

3. Irrespective of h_s, M and the spacing between buildings, a narrow adjacent building (upstream or downstream) has minimal influence on the plume trajectory as opposed to wider adjacent buildings. In such cases, the emitting building is equivalent to an isolated building.

4. Rooftop dilution on the emitting building gradually increases (towards the isolated building case) as the spacing between buildings exceeds the recirculation length of the upstream building.

5. Buildings of lower or similar height as the emitting building have minimal influence on the plume characteristics irrespective of h_s, M and the spacing between buildings.

6. The presence of a taller upstream building and a taller downstream building increases the rooftop concentration of pollutant on the emitting building, due to the back and forth movement of the plume.

7.2.2 ASHRAE provisions

1. ASHRAE 2007 estimates yield lower dilutions than the experimental findings and are therefore overly conservative. ASHRAE 2011 predictions compare well with isolated building for low M values ($M < 3$).

2. In general, ASHRAE provisions are less suited, when applied to multiple building configurations.

3. The current ASHRAE provisions must be re-visited. In particular, the formulations must incorporate the effect of neighbouring buildings, besides developing formulations to estimate dilutions on adjacent building surfaces.

7.2.3 Rectified ASHRAE 2007 approach

1. The rectified ASHRAE 2007 approach utilises the wind tunnel results of the present study as well as the ASHRAE estimates to propose certain factors which can be applied to obtain realistic dilution estimates.

2. The factors can be applied to estimate dilution on emitting and adjacent building surfaces and provide reasonable estimates when applied to the present and previous experimental studies.

7.2.4 Occupational health and safety considerations

ASHRAE 2011 suggests a minimum exhaust speed of 10 m/s to generate higher dilutions irrespective of the nature of the exhaust (laboratory fumes or residential building exhaust). Results from the present study show that for adjacent building configurations, a stack height of 3 m (or higher) at $M > 2$ produces higher dilutions that less affects the wake of the emitting building and surfaces of the adjacent building. Future ASHRAE versions must specifically state the necessary criteria for safety of laboratory workers and residential building occupants. Some of these criteria may include the ‘nature’ and ‘acceptable concentrations’ of exhaust emitted from a building; specifying the spacing between buildings and the location of intakes on a building surface to avoid plume re-ingestion (e.g. Figure 6.1). According to Hori, 2012, "*In terms of safety and health in the workplace, the insufficiency of management and ineffective regulations has created problems that have only resulted in disaster. Ironically, such disasters have influenced administrators and government officials to enforce effective changes that have resulted in overall advancements in the workplace. Perhaps more research on such positive effects in addition to the prevention against psychological and physical issues in the workplace should be considered in the future*."

7.3 Recommendations for future research

The present study focuses on near-field pollutant dispersion from rooftop emissions for various adjacent building configurations. Future researchers can investigate the following issues:

a. Emitting buildings with rooftop structures may be tested in the wind tunnel in the presence of adjacent buildings, as the present study only focussed on buildings with flat roofs. Rooftop structures are known to increase rooftop concentrations for isolated buildings (Gupta *et al.* 2012).

b. Results of the present study were restricted to a near-neutral stability condition. It is known that atmospheric stability can affect the effluent dispersion phenomena for isolated buildings (Li and Meroney, 1983). Hence, studying the effect of near-field pollutant dispersion for different atmospheric conditions in a thermally stratified wind tunnel would be an interesting endeavour.

c. The results of this study included only a single upstream or downstream building. However, in a densely populated urban environment a cluster of buildings is more likely to exist. Therefore, future researchers should increase the number of buildings in the vicinity of the source to simulate a more realistic situation.

d. Very few wind tunnel tracer studies (such as Gromke *et al.* 2008) have investigated the effects of tree plantation on near-field dispersion. A detailed study in this direction could be of great interest for future experimentalists.

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APPENDIX A

ASHRAE MODELS

A1. General

This appendix describes the ASHRAE (2007 and 2011) models. Both models are semi Gaussian in nature and can be applied to estimate roof dilutions for exhausts released from a rooftop stack.

A2. ASHRAE 2007

ASHRAE 2007 has devised two techniques:

a) Geometric design method;

b) Gaussian plume equations.

The former is used to assess the height of the stack required to avoid plume re-ingestion, while the latter is used to estimate plume dilutions on a given rooftop receptor. Additional details for the geometric design method can be found in Stathopoulos *et al.* (2008). In this appendix, only the Gaussian approach is discussed.

Gaussian plume equations

The dimensions of flow re-circulation zones that form on the building and Roof Top Structure (RTS) are:

$$L_r = B_s^{0.67} B_L^{0.33} \tag{A.1}$$

where B_s is the smallest and B_L the largest dimension of building face normal to wind

$$H_c = 0.22 L_r \tag{A.2}$$

$$X_c = 0.5 L_r \tag{A.3}$$

$$L_c = 0.9 L_r \tag{A.4}$$

where:

H_c is the maximum height of the roof recirculation zone (m),

X_c is the distance from the leading edge to H_c (m),

L_c is the length of the roof recirculation zone (m).

Some of the parameters required for assessing dilution include the effective height of the plume (h_{plume}) above the roof:

$$h_{plume} = h_s + h_r - h_d \tag{A.5}$$

where:

h_s is stack height (m),

h_r is plume rise (m),

h_d is the reduction in plume height due to entrainment into the stack wake during periods of strong winds (m).

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

$$h_r = 3\beta d_e (V_e / U_H) \tag{A.6}$$

where:

d_e is the stack diameter (m),

V_e is the exhaust velocity (m/s),

U_H is the wind speed at building height (m/s),

β is the stack capping whose value is 1 for uncapped and 0 for capped stacks.

The effect of plume buoyancy is not taken into account.

Wilson *et al.* (1998) recommended a stack wake downwash adjustment h_d, which is defined as:

$$h_d = d_e (3 - \beta V_e / U_H) \tag{A.7}$$

The dilution D_r is defined as:

$$D_r = C_e/C_r \tag{A.8}$$

where:

C_e is the contaminant mass concentration in exhaust (kg/m^3),

C_r is the contaminant mass concentration in receptor (kg/m^3).

The spread parameters (standard deviations of the plume) are described as follows:

$$\sigma_y / d_e = 0.071\left(t_{avg} / 2\right)^{0.2} (X / d_e) + \sigma_o / d_e \qquad \text{(A.9)}$$

$$\sigma_z / d_e = 0.071(X / d_e) + \sigma_o / d_e \qquad \text{(A.10)}$$

where:

t_{avg} is the concentration averaging time in minutes,

X is the distance downwind from the stack (m),

σ_y and σ_z are standard deviations of the plume (m),

σ_o is the initial source size that accounts for stack diameter and for dilution jet entrainment during plume rise (m).

An averaging time (t_{avg}) of 2 minutes was used for estimating dilutions, because ASHRAE 2007 states *"For the case of both stack tip and air intake in the same wind recirculation zone, assume the D_r values for 2 min averages also apply for all averaging times from 2 to 60 min."*

The dependence of initial spread σ_o on exit velocity to wind speed ratio V_e / U_H is

$$\sigma_o / d_e = \left[0.125\beta(V_e / U_H) + 0.911\beta(V_e / U_H)^2 + 0.25\right]^{0.5} \qquad \text{(A.11)}$$

As per ASHRAE 2007, dilution at roof level in a Gaussian plume emitted at the final rise plume height is:

$$D_r = 4(U_H / V_e)(\sigma_y / d_e)(\sigma_z / d_e)\exp(\zeta^2 / 2\sigma_z^2) \qquad \text{(A.12)}$$

where:

ζ is the vertical separation between h_{plume} and H_c

$\zeta = h_{plume} - H_c$ if $h_{plume} > H_c$

$\zeta = 0$ if $h_{plume} \leq H_c$

For all cases the dilution calculated from Equation A.12 has been converted to a normalised form according to Wilson *et al.* (1998) for ease of comparison with previous studies:

$$D_{normalised} = (D_r\ Q) / (U_H\ H^2) \qquad \text{(A.13)}$$

A3. ASHRAE 2011

ASHRAE 2011 has introduced changes to estimate plume rise (h_r), plume spread parameters (σ_y and σ_z) and dilution for shorter time periods. Plume rise (h_r) is estimated as

$$h_r = \min\{\beta h_x, \beta h_f\} \tag{A.14}$$

where:

β is the stack capping factor: 1 without cap, 0 with cap,

h_x and h_f are estimated as

$$h_x = \left(\frac{3V_e^{\,2} d_e^{\,2} x}{4\beta_j^{\,2} U_H^{\,2}}\right)^{1/3} \tag{A.15}$$

$$h_f = \frac{0.9[(V_e^{\,2} d_e^{\,2}/4)(U_H/U_*)]^{0.5}}{\beta_j U_H} \tag{A.16}$$

where:

U_* is the friction velocity (m/s),

β_j is termed as the jet entrainment coefficient and is calculated as

$$\beta_j = \frac{1}{3} + \frac{U_H}{V_e} \tag{A.17}$$

The logarithmic wind profile equation is

$$U_H / U_* = 2.5 \ln(H / Z_o) \tag{A.18}$$

where:

H is the height of the building (m),

Z_o is the surface roughness length (m).

The plume spread parameters (σ_y and σ_z) are calculated using the formulations of Cimoreli *et al.* (2005):

$$\sigma_y = (i_y^{\,2} X^2 + \sigma_0^{\,2})^{0.5} \tag{A.19}$$

$$\sigma_z = (i_z^{\,2} X^2 + \sigma_0^{\,2})^{0.5} \tag{A.20}$$

$$i_x = [0.24 + 0.096\log(Z_o) + 0.016(\log Z_o)^2][\ln(30/Z_o)/\ln(H/Z_o)] \qquad \text{(A.21)}$$

$$i_y = 0.75 i_x \qquad \text{(A.22)}$$

$$i_z = 0.5 i_x \qquad \text{(A.23)}$$

where:

i_x, i_y *and* i_z are the turbulence intensities in x, y and z directions, respectively,

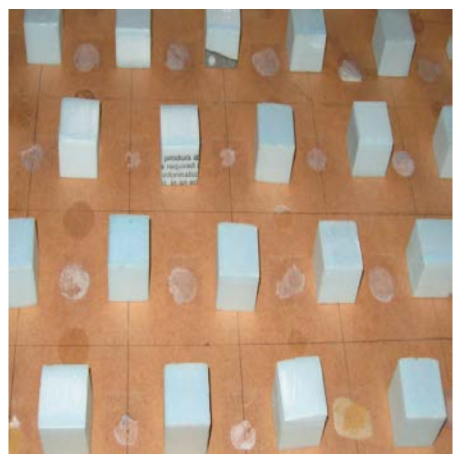
σ_o is the initial source size and is set equal to $0.35d_e$ (m),

H is the height of the building (m).

ASHRAE 2011 also suggests that dilution calculations must be carried out for three different roughness lengths (Z_o), namely: $0.5Z_o$, $1.5Z_o$ and Z_o, and the lowest dilution value must be chosen for the design.

APPENDIX B
WIND TUNNEL FOR TRACER STUDIES AT CONCORDIA

[a] Spires that act as vortex generators

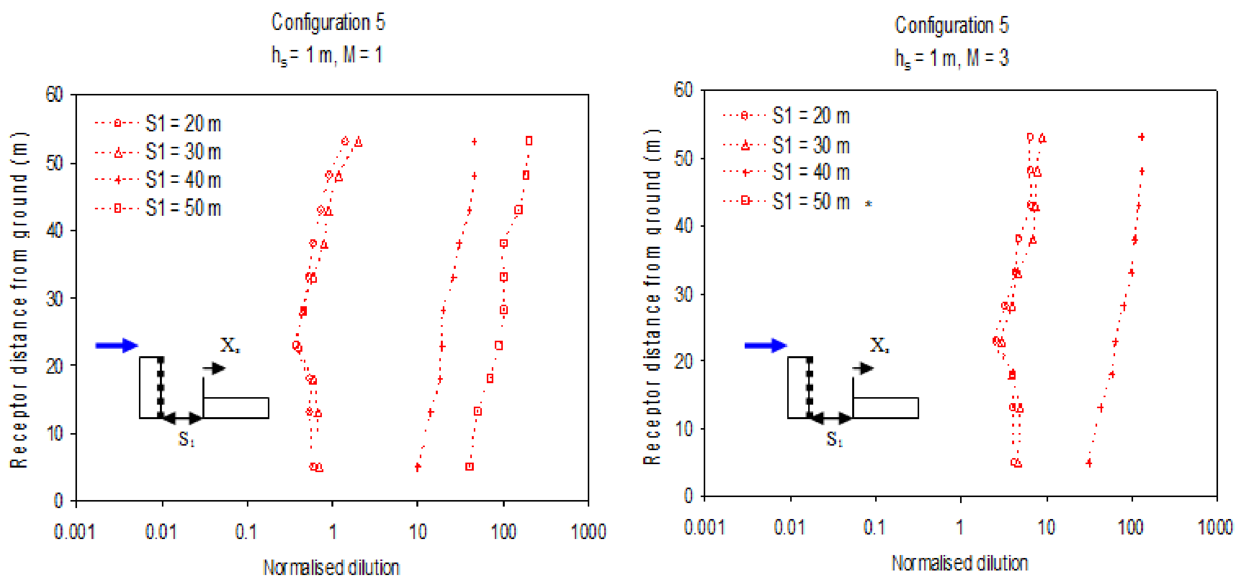


[b] Cubes to generate an urban terrain

Figure B – Front view section of the boundary layer wind tunnel at Concordia University.

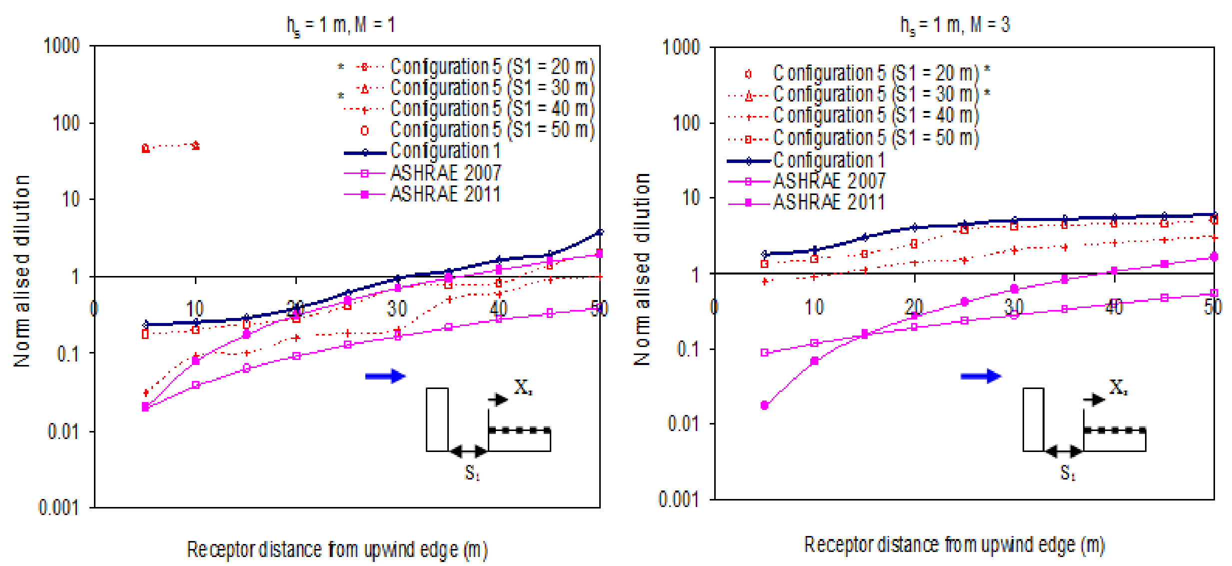
APPENDIX C
ADDITIONAL RESULTS FOR UPSTREAM BUILDING CONFIGURATIONS

The effects of spacing for a taller upstream building configuration (Configuration 5) is presented for the leeward wall of the taller upstream building (Figure C1) and roof of the low building with source (Figure C2).



a) b)

Figure C1 – Normalised dilution on leeward wall of B_5 for different spacing (S_1) at $X_s = 0$ and $h_s = 1$ m: a) M = 1; b) M = 3. * Concentration of pollutants was found to be zero

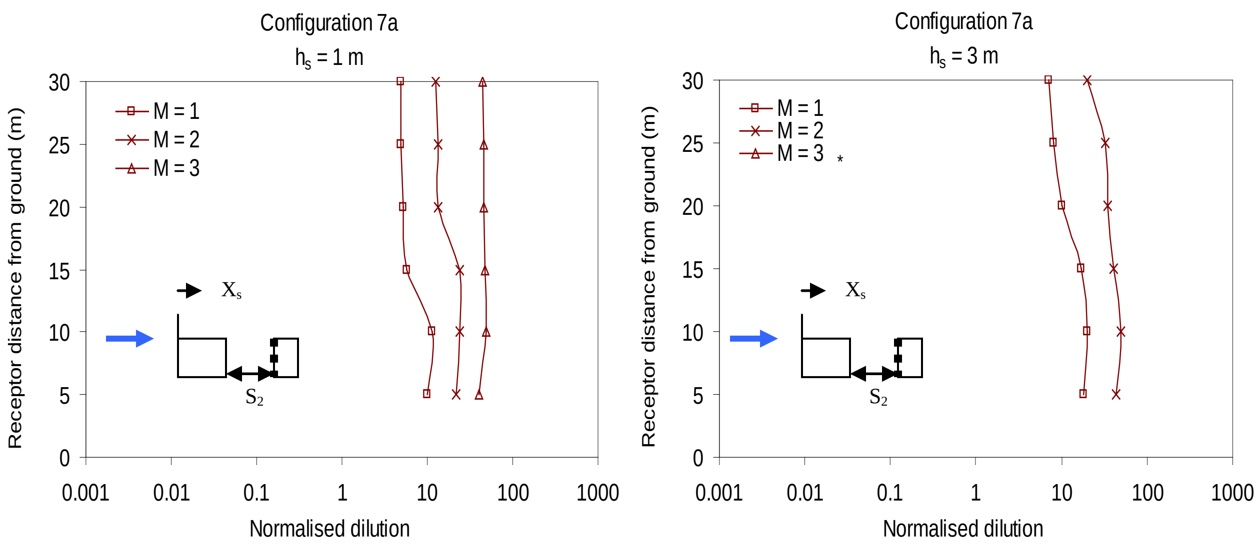


a) b)

Figure C2 – Normalised dilution on rooftop of B_1 for different spacing (S_1), $X_s = 0$ and $h_s = 1$ m: a) M = 1; b) M = 3. * Concentration of pollutants was found to be zero

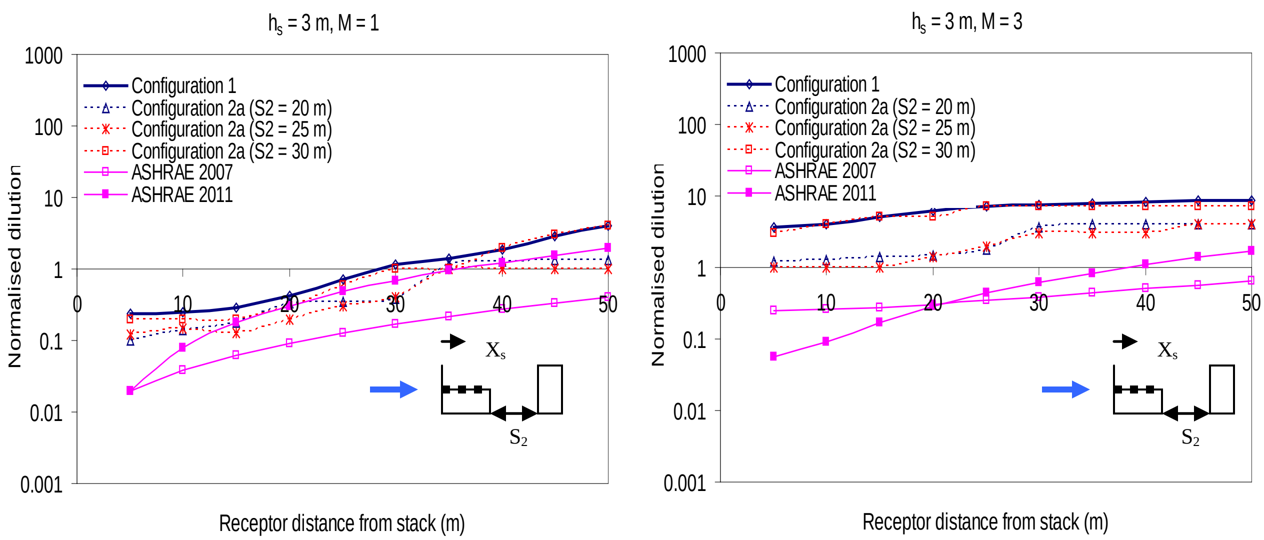
APPENDIX D
ADDITIONAL RESULTS FOR DOWNSTREAM BUILDING CONFIGURATIONS

Dilution results for buildings of equal height (Figure D1) and the effect of spacing between buildings for taller downstream configurations (Figure D2) are presented.



a) b)

Figure D1 – Normalised dilution on windward wall of B_2 for S_2 = 20 m and X_s = 0: a) h_s = 1 m; b) h_s = 3 m. * Pollutant concentrations were found to be zero at all receptors

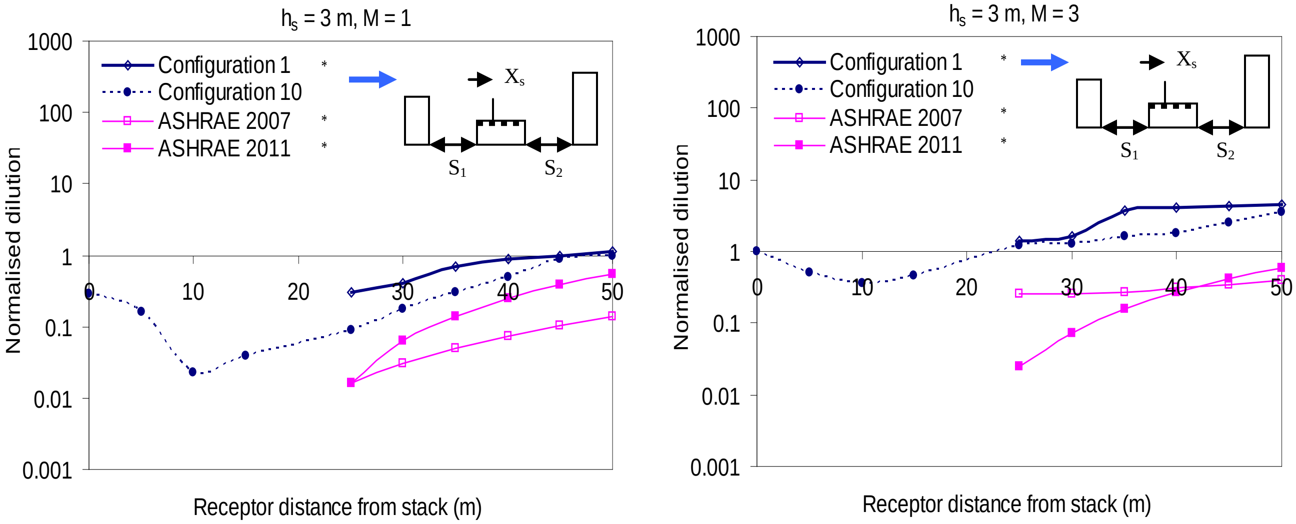


a) b)

Figure D2 – Normalised dilution on rooftop of B_1 for h_s = 3 m and X_s = 0: a) M = 1; b) M = 3.

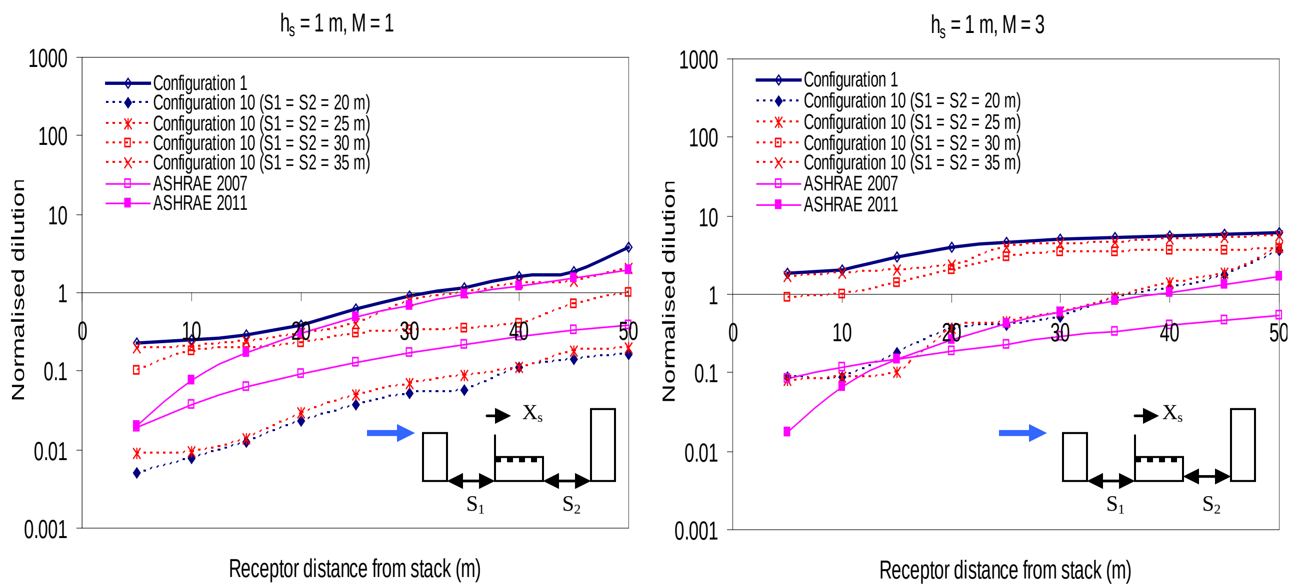
APPENDIX E
ADDITIONAL RESULTS FOR CONFIGURATIONS 10 AND 11

Configuration 10 consists of a low building with source, in the presence of a taller upstream and a taller downstream building. Configuration 11 consists of an upstream building which is of equal height as the emitting building, and a taller downstream building. The effect of a centrally placed stack for Configuration 10 for spacing between buildings $S_1 = S_2 = 20$ m, is presented in Figure E1. Effect of a change in spacing between buildings for Configuration 10 is presented in Figure E2. Roof dilutions for the emitting and downstream buildings of Configuration 11 are presented in Figures E3 and E4 respectively.



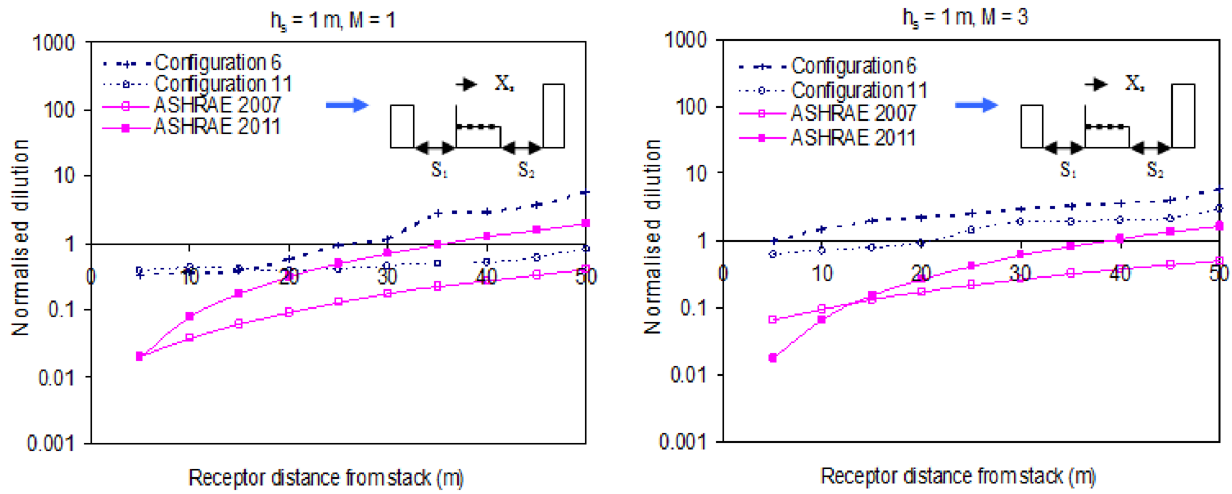
a) b)

Figure E1 – Normalised dilution on rooftop of B_1 for h_s = 3 m and X_s = 20 m: a) M = 1; b) M = 3. * pollutant concentration was zero at receptors upwind of stack



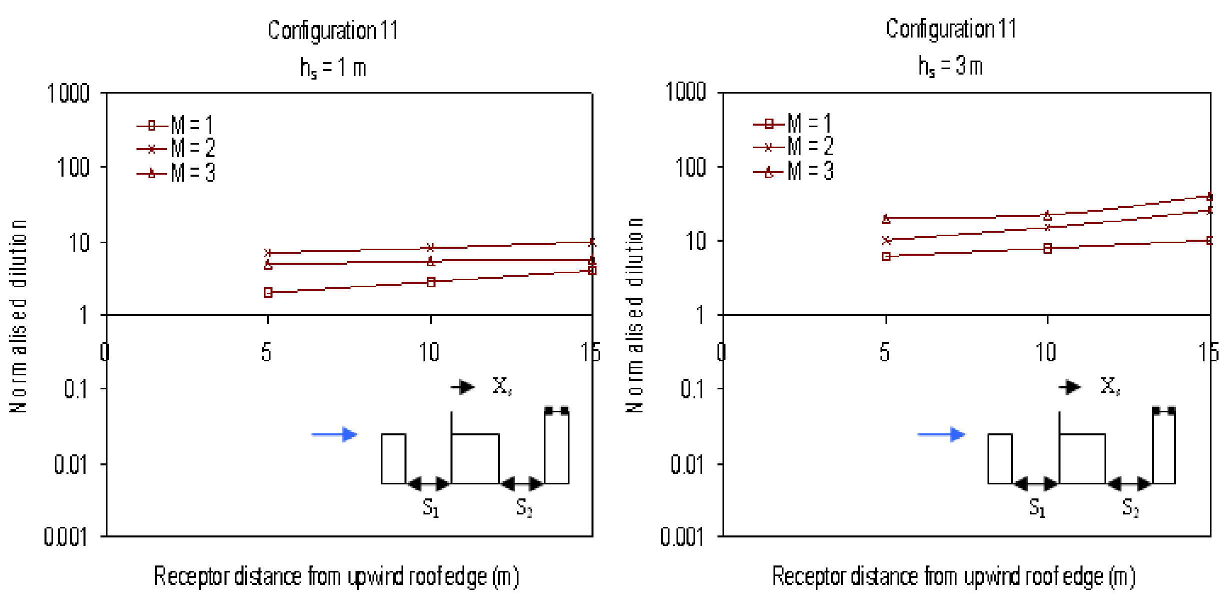
a) b)

Figure E2 – Normalised dilution on rooftop of B_1 for X_s = 0: a) M = 1; b) M = 3.



a) b)

Figure E3 – Normalised dilution on rooftop of B_6 for $X_s = 0$ and $S_1 = S_2 = 20$ m: a) M = 1; b) M = 3.

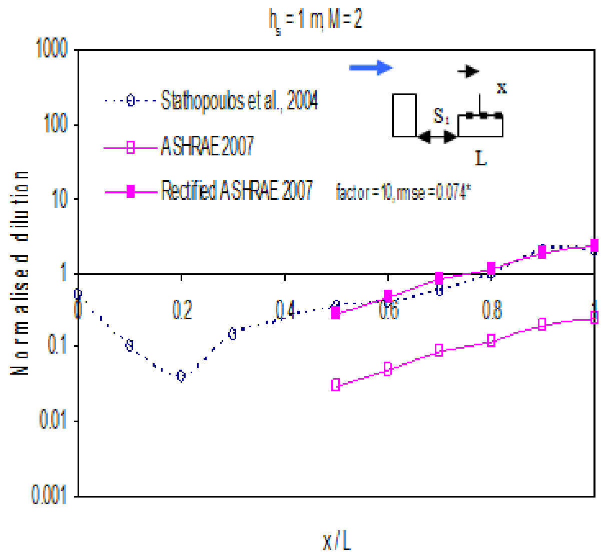


a) b)

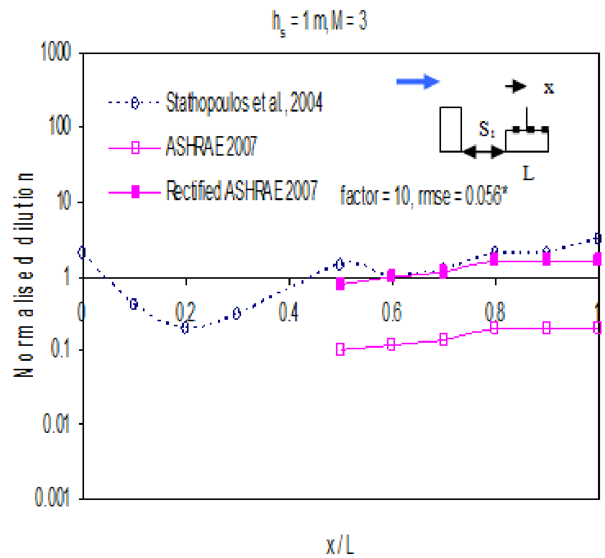
Figure E4 – Normalised dilutions on rooftop of B_5 for $X_s = 0$ and $S_1 = S_2 = 20$ m: a) $h_s = 1$ m; b) $h_s = 3$ m.

APPENDIX F
ADDITIONAL RESULTS FOR THE APPLICATION OF RECTIFIED ASHRAE 2007 MODEL

Application of the Rectified ASHRAE 2007 approach on field data obtained from Stathopoulos *et al.* (2004) for roof (Figure F1) and wall (Figure F2) dilutions are presented. Comparisons with experimental data from Wilson *et al.* (1998) and rectified ASHRAE 2007 estimates for an isolated building (Figure F3) and for a taller downstream configuration (Figure F4) are also presented.

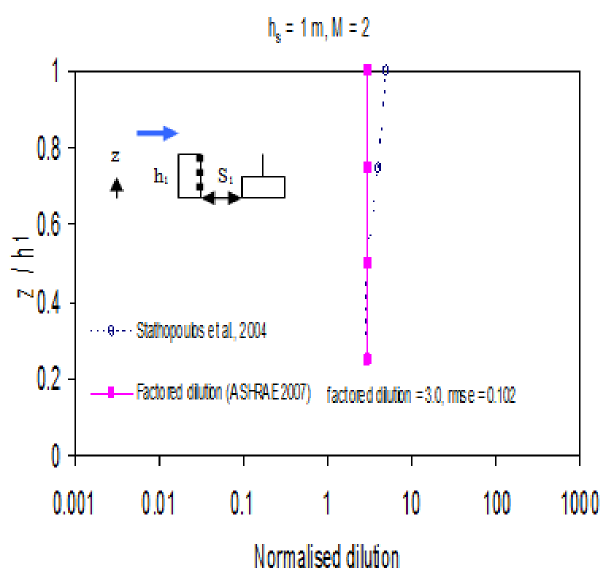


a)

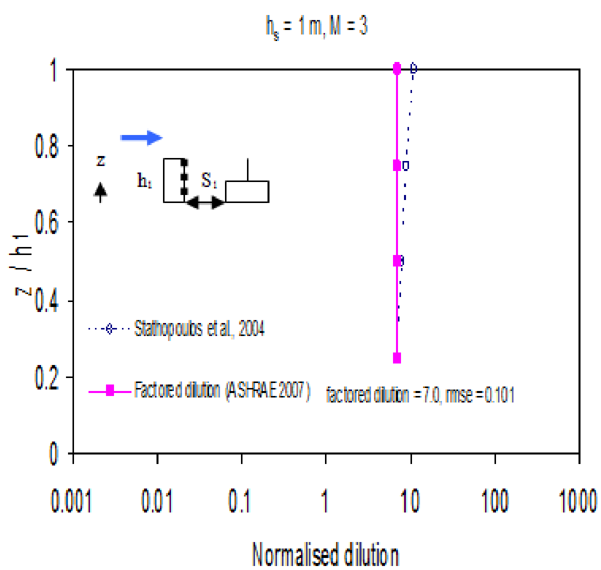


b)

Figure F1 – Model validation with field data from Stathopoulos *et al.* (2004) for the low-rise building for X_s = 0.4L: a) M = 2; b) M = 3. * rmse was evaluated using the wind tunnel and rectified ASHRAE model, only for receptors downwind of stack (6 receptors)

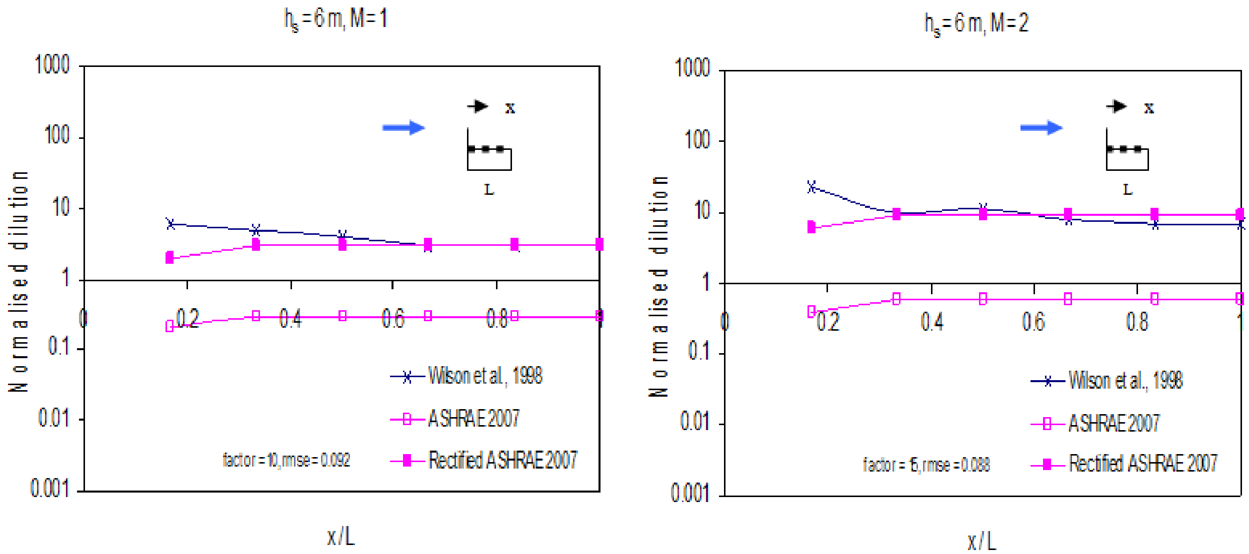


a)



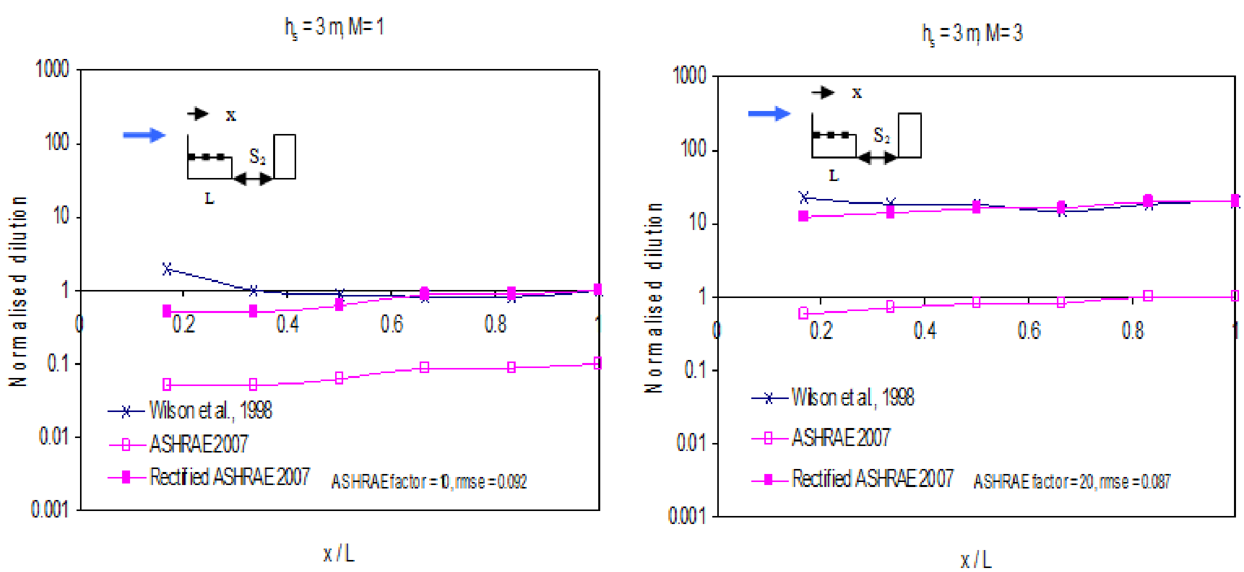
b)

Figure F2 – Normalised dilution on leeward wall of upstream building: a) M = 2; b) M = 3.



a) b)

Figure F3 – Validation with wind tunnel data from Wilson *et al.* (1998) for a flat roofed low-rise building, for X_s = 0: a) M = 1; b) M = 2.



a) b)

Figure F4 – Validation with wind tunnel data from Wilson *et al.* (1998) for a flat roofed low building with source, for X_s = 0: a) M = 1; b) M = 3.