Fresh air intakes contamination: Problem identification and prevention

by

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Introduction

- Outdoor air pollution is one of the major environmental problems today.

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• Sources:
- Residential and office buildings
- Traffic
- Industrial installations
- Power plants
- Agriculture






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• Various types of pollutants:
  - Particulate matter (PM)
  - Carbon monoxide (CO)
  - Carbon dioxide (CO_2)
  - Oxides of nitrogen and sulphur (NO_x, SO_x)
  - Formaldehyde (H_2CO)
  - Ozone (O_3)
  - Polycyclic aromatic hydrocarbons (PAH)

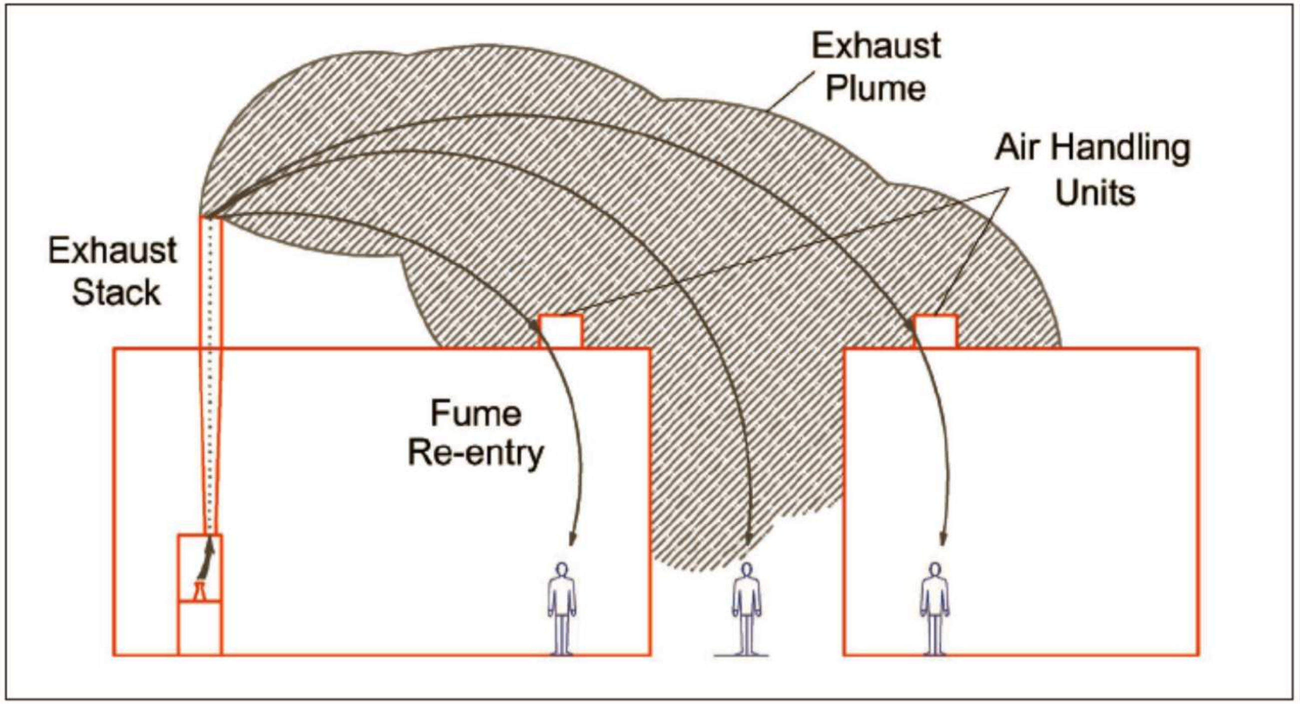
• Broad spectrum of acute and chronic health effects:
(Brunekreef and Holgate, 2002, Cohen et al. 2005, Peters, 2005, Xia and Tong, 2006).
  - Respiratory disease
  - Cardiovascular disease
  - Mortality

• Brunekreef and Holgate (in *The Lancet*, 2002) mention that these effects have been seen even at very low levels of exposure, and that it is **unclear whether a threshold concentration exists** for e.g. particulate matter and ozone below which no effects on health are likely.

Introduction

- In the built environment: outdoor exposure of pedestrians and indoor exposure of building inhabitants (**micro-scale** pollutant dispersion: L < 5 km)

  - Drivas et al. 1972 mentioned that in one case 20% of the exhausted fumes re-entered the ventilation system of the building.
  - Moon et al. 1997 reported ventilation intake pollution episodes in a day-care facility that were serious enough to cause building evacuation.



(after Petersen et al. 2002)

Outline

- **Introduction**
- **How to assess pollutant concentration**
  - ASHRAE Semi-empirical Methodology
  - Wind Tunnel Experiments
  - Field Experiments
  - Numerical Methods (CFD)
  - EPA Approved Dispersion Models
- **IRSST and Collaborative project with Concordia**
- **Design guidelines**
  - Codes and Standards
  - ASHRAE
  - Additional Guidelines
- **Conclusions**

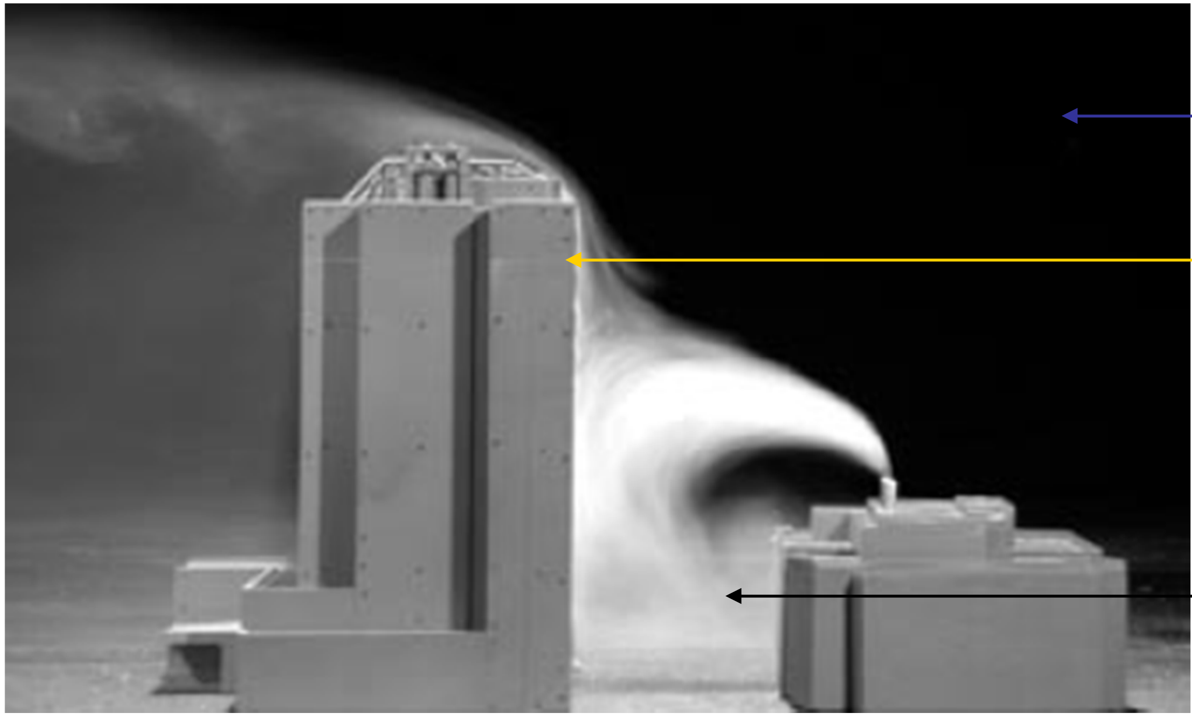
Questions Faced by a Designer

- How to assess pollutant concentration (which method/model to adopt ?)

- How to determine the location of stack and intake ?

- What should be the correct stack height ?

Downwash Affecting the Building itself and an Adjacent Building



Wind direction

Downwash affecting a neighbouring building

Downwash forcing pollutants to re-enter the building

From: http://www.epa.gov/lab21gov/pdf/bp_modeling_508.pdf

How to Assess Pollutant Concentration ?

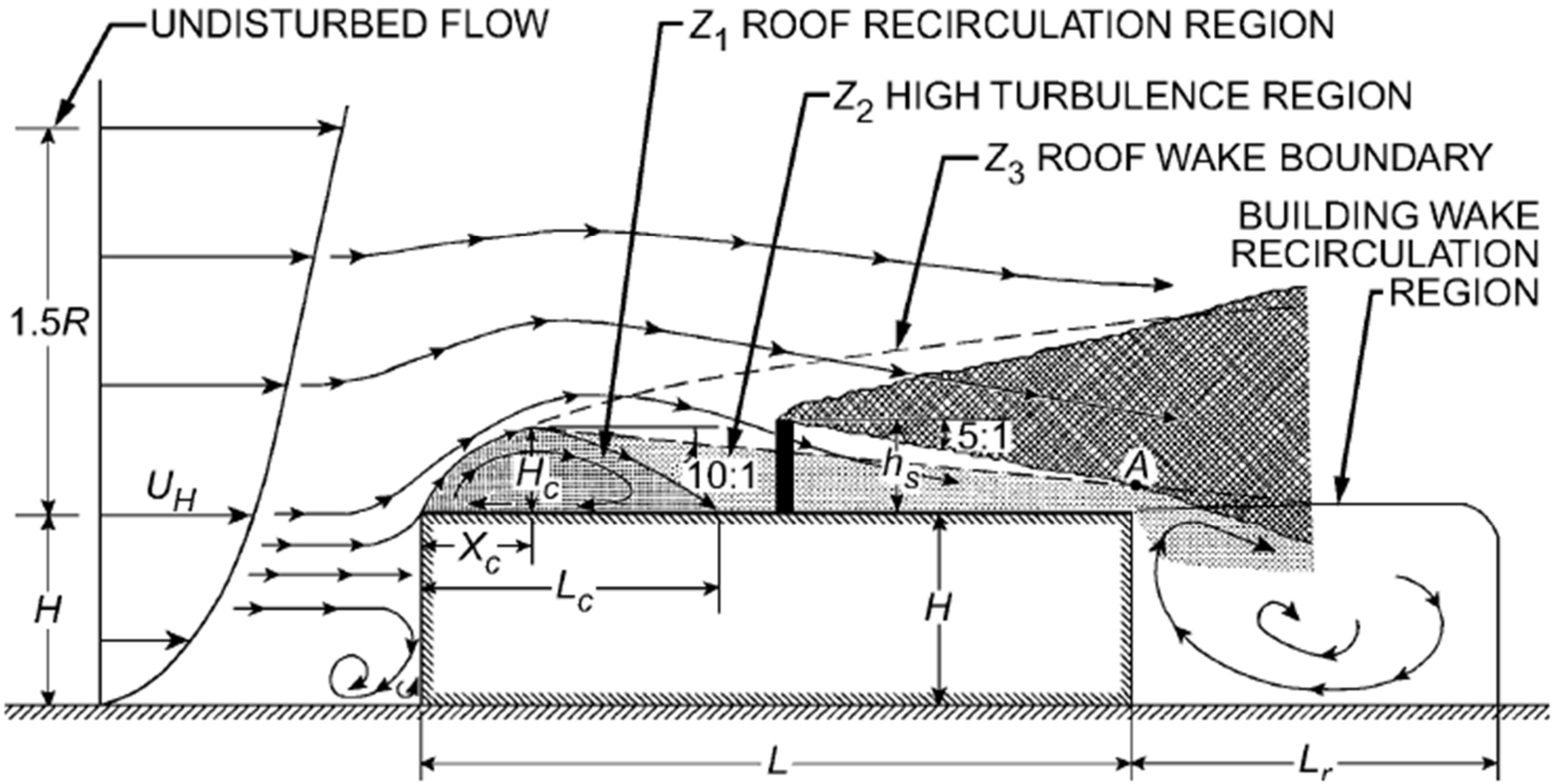
- ASHRAE
- Wind Tunnel Experiments
- Field Measurements
- Numerical Methods
- EPA Approved Dispersion Models

ASHRAE Dispersion Models

ASHRAE Dispersion Models

- Geometric Design Method
- Gaussian Plume Equations for Roof-level Dilutions

Geometric Design Method



Design procedure for required stack height to avoid contamination [from Wilson, 1979]

- The effective height of the plume above the roof or rooftop structure is
- $h = h_s + h_r - h_d$
- h_s is stack height,
- h_r is plume rise = $3\beta d_e(V_e/U_H)$ - Briggs,1984,
- h_d is the reduction in plume height due to entrainment into the stack wake during periods of strong winds

Gaussian Plume Equations For Roof Level Dilutions

Results may be expressed as Concentrations or Dilutions

$D = C_e / C$

C_e = contaminant mass concentration in exhaust, lb/ft^3
C = contaminant mass concentration at receptor, lb/ft^3

The exhaust (source) concentration is given by
$C_e = m / Q_e = m/(A_e V_e)$

where
m= contaminant mass release rate, lb/s
$Q_e = A_e V_e$ = total exhaust volumetric flow rate, ft^3/s
A_e = exhaust face area, ft^2
V_e = exhaust face velocity, ft/s

- Dilutions can be expressed as a function of the wind speed and exhaust velocity:

$$D_r = 4\frac{U_H}{V_e}\frac{\sigma_y}{d_e}\frac{\sigma_z}{d_e}\exp\left[\frac{h^2}{2\sigma_z^2}\right]$$

$$\frac{\sigma_y}{d_e} = 0.071\left(\frac{t_{avg}}{2.0}\right)^{0.2}\frac{X}{d_e} + \frac{\sigma_o}{d_e}$$

$$\frac{\sigma_z}{d_e} = 0.071\frac{X}{d_e} + \frac{\sigma_o}{d_e}$$

σ_y cross-wind plume spread

σ_z vertical plume spread

where:

t_{avg} is the concentration averaging time in minutes,
X is the distance downwind from the stack,

ASHRAE 2007

- There are very few changes from the earlier version of ASHRAE 2003

- The following formula is used to find Dilution as per ASHRAE 2007:

$$D_r = 4\frac{U_H}{V_e} \times \frac{\sigma_y}{d_e} \times \frac{\sigma_z}{d_e} \exp\left(\frac{\xi^2}{2\sigma_z^{\ 2}}\right)$$

$$\text{where } \xi = h_{plume} - h_{Top}$$
$$= 0 \qquad\qquad \text{if } h_{plume} < h_{Top}$$

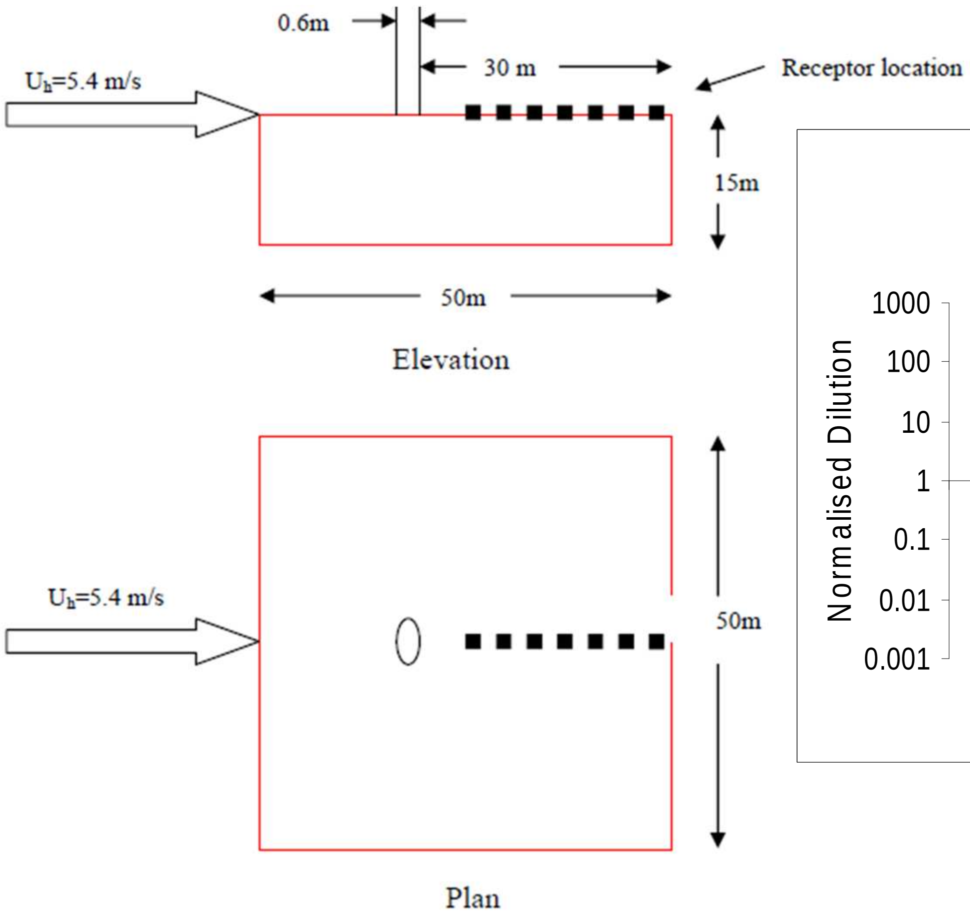
Merits of ASHRAE Model

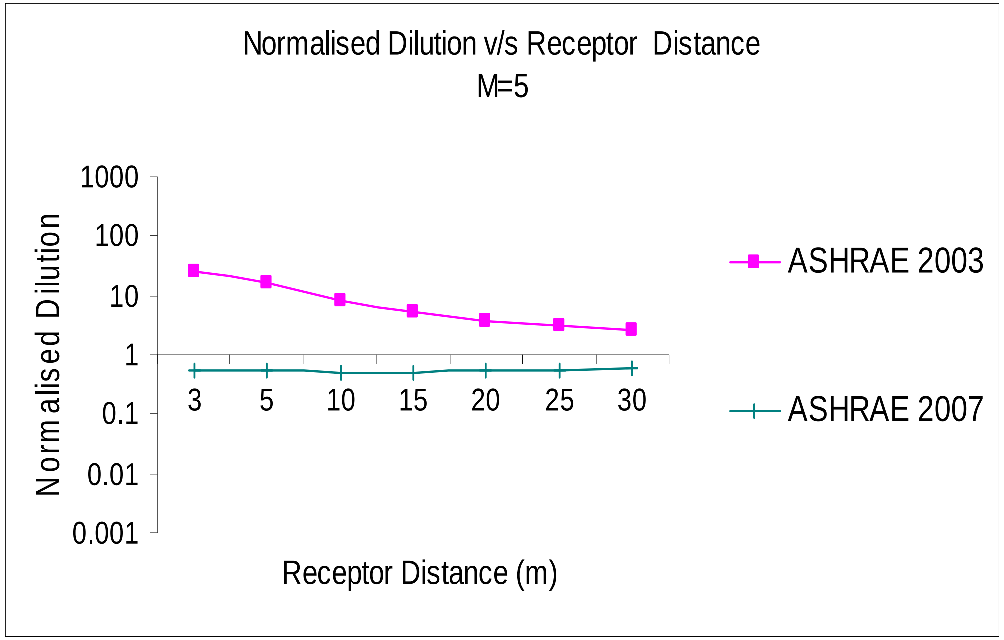
- Particularly useful for near-field dispersion problems of isolated buildings
- Building and stack downwash are taken into account
- Separate formulations are provided for capped and uncapped stacks
- ASHRAE can model the effects of rooftop structure
- ASHRAE 2007 is easier to use compared to the 2003 version because of its simplified language and formulations.

Demerits of ASHRAE Model

- Both 2007 and 2003 versions do not consider effects of building geometry and size, neighbouring buildings, change in terrain characteristics and wind direction.

- In general, the 2007 version estimates higher pollutant concentrations than the 2003 version.





Stathopoulos et al. 2008

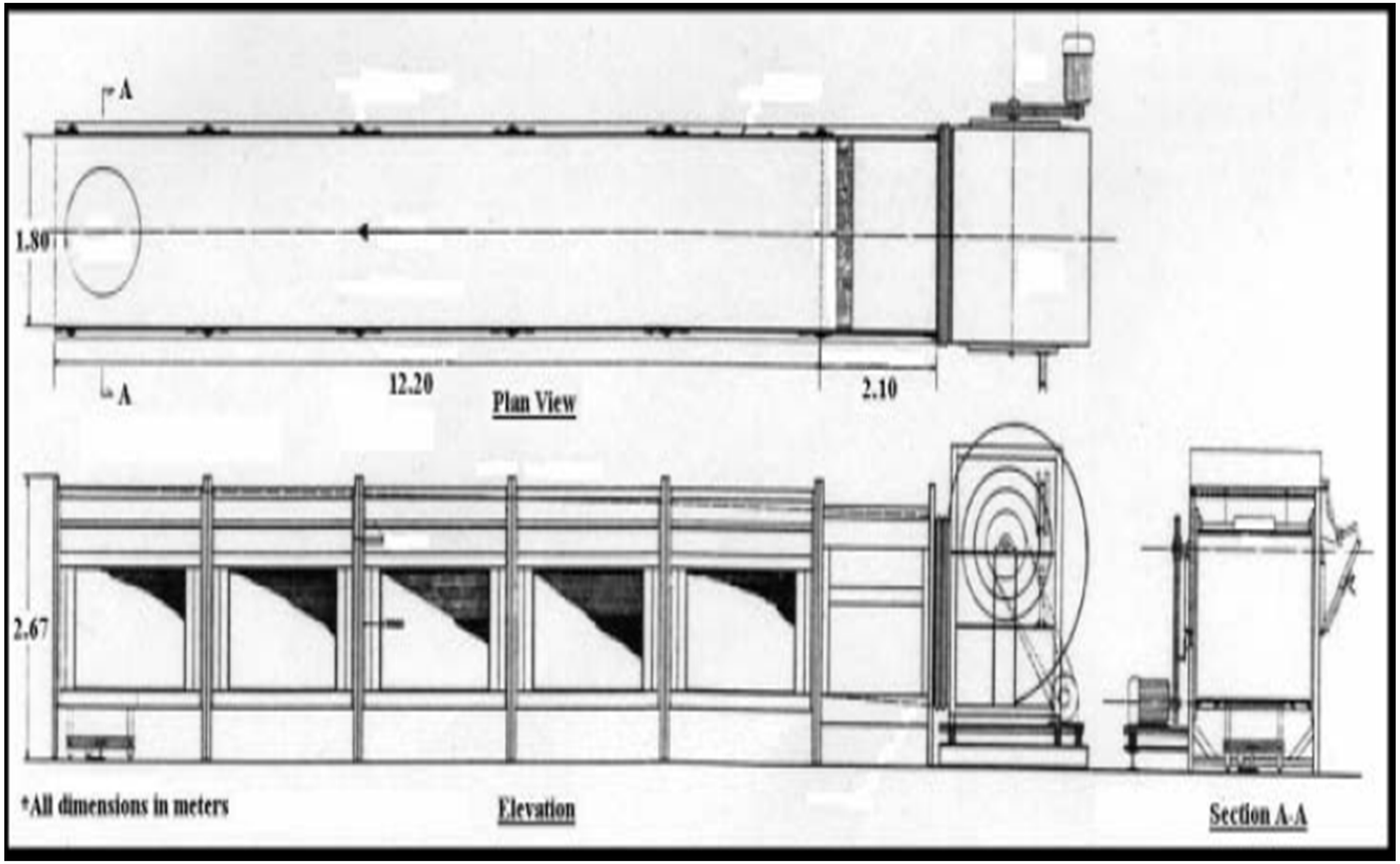
Wind Tunnel Experimentation

Wind Tunnel Experimentation

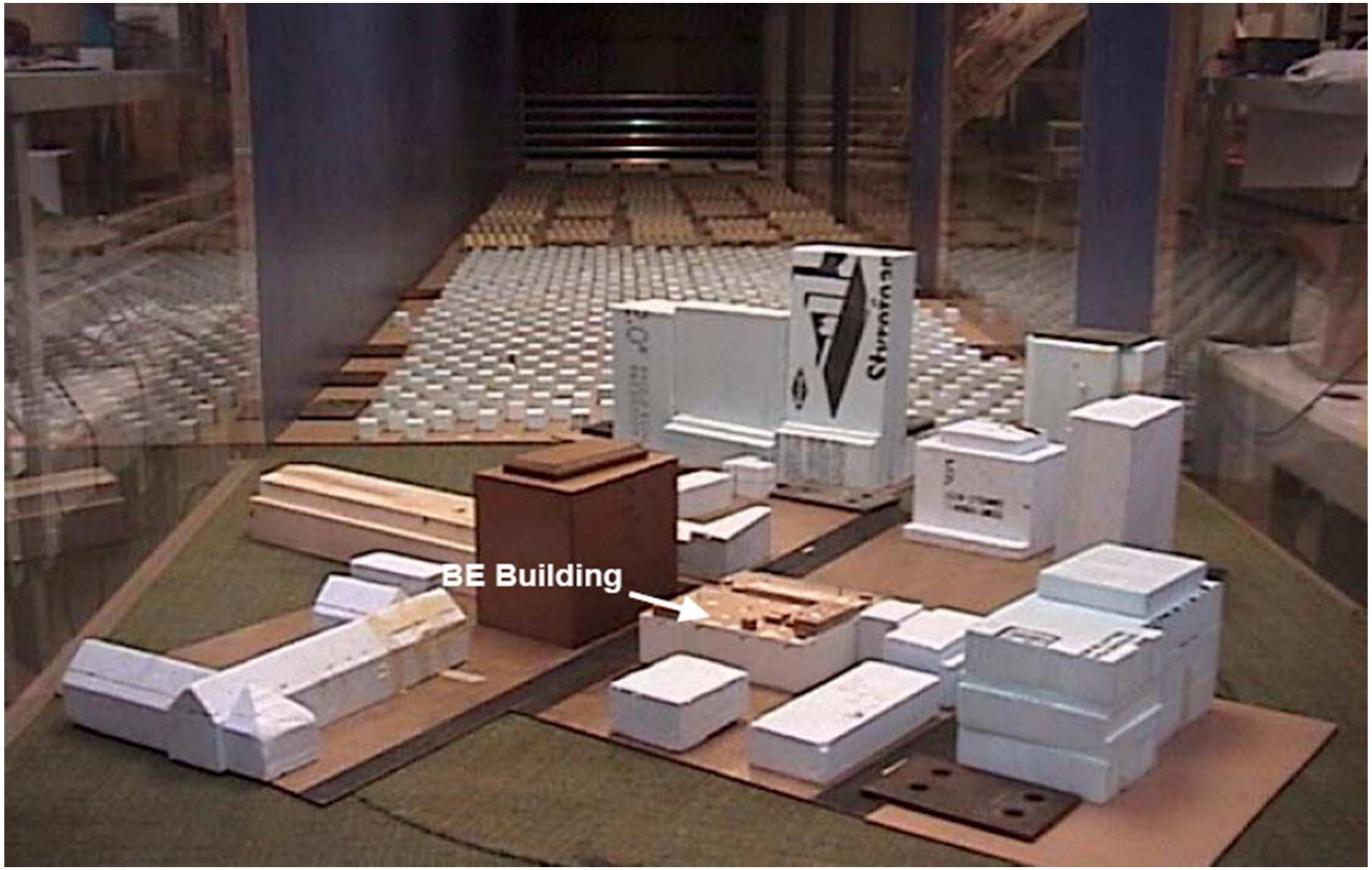
- Wind tunnels simulate wind flow around building models
- Physical simulation requires a particular geometric scale for modelling the building and its surroundings
- Wind tunnels are used for studying all wind-building/structure interaction problems such as:
  - Wind loads on structures
  - Pedestrian wind studies
  - Pollutant dispersion studies
  - Flow visualisation

Wind Tunnel at Concordia University

Front view



Concordia University boundary layer wind tunnel



Wind tunnel set up

Merits of Wind Tunnel Modelling

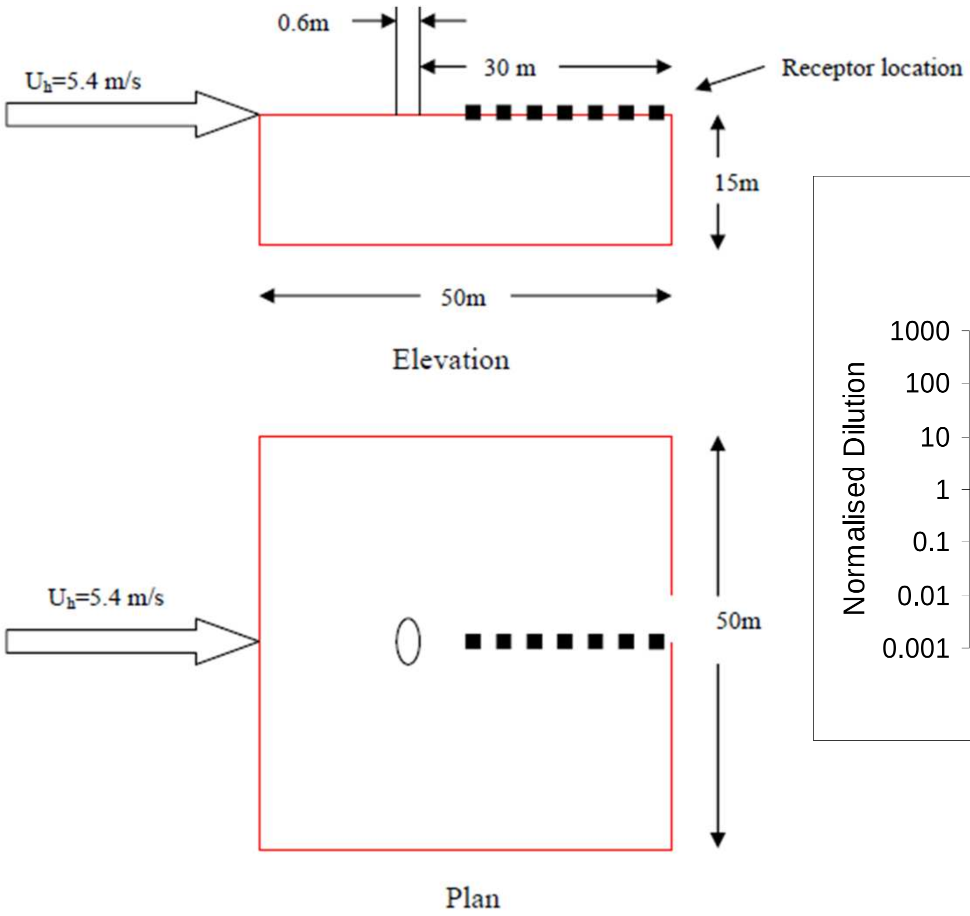
- It simulates air flow patterns around complex building configurations
- It may account for the effect of surrounding structures, local topography and different upstream conditions (upwind velocity profiles)
- Most accurate method of predicting dispersion of pollutants and impacts from building exhausts

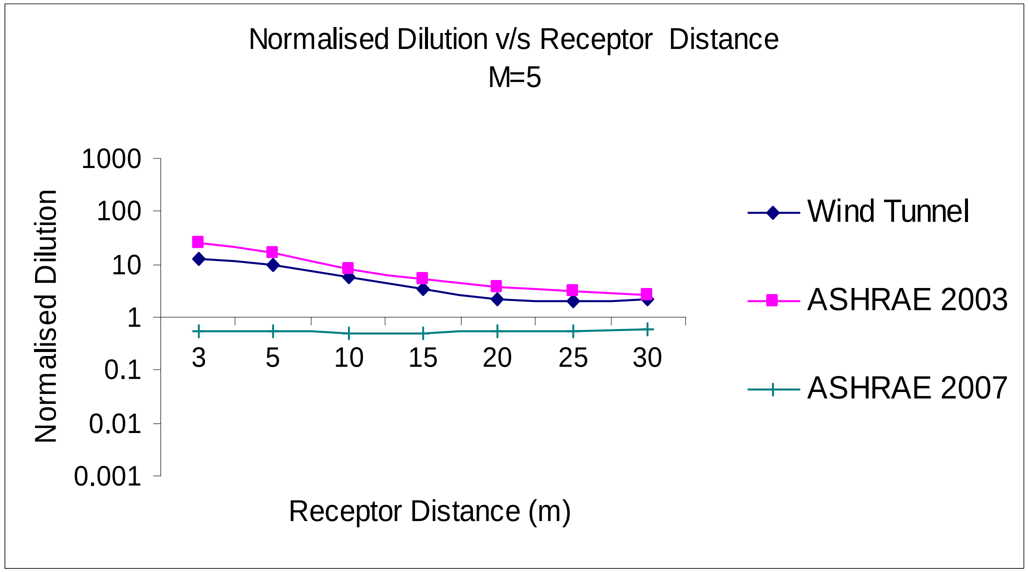
Demerits of Wind Tunnel Modelling

- Building models of large sizes (scales) can block air flow, resulting in inaccurate modelling of actual flow conditions

- Buildings with curved surfaces are difficult to be modelled due to Re effects

- Building architectural details including rooftop structures, balconies, mullions, may be difficult to model on a smaller scale


0.6m
30 m
Receptor location
U_h=5.4 m/s
15m
50m
Elevation
U_h=5.4 m/s
50m
Plan

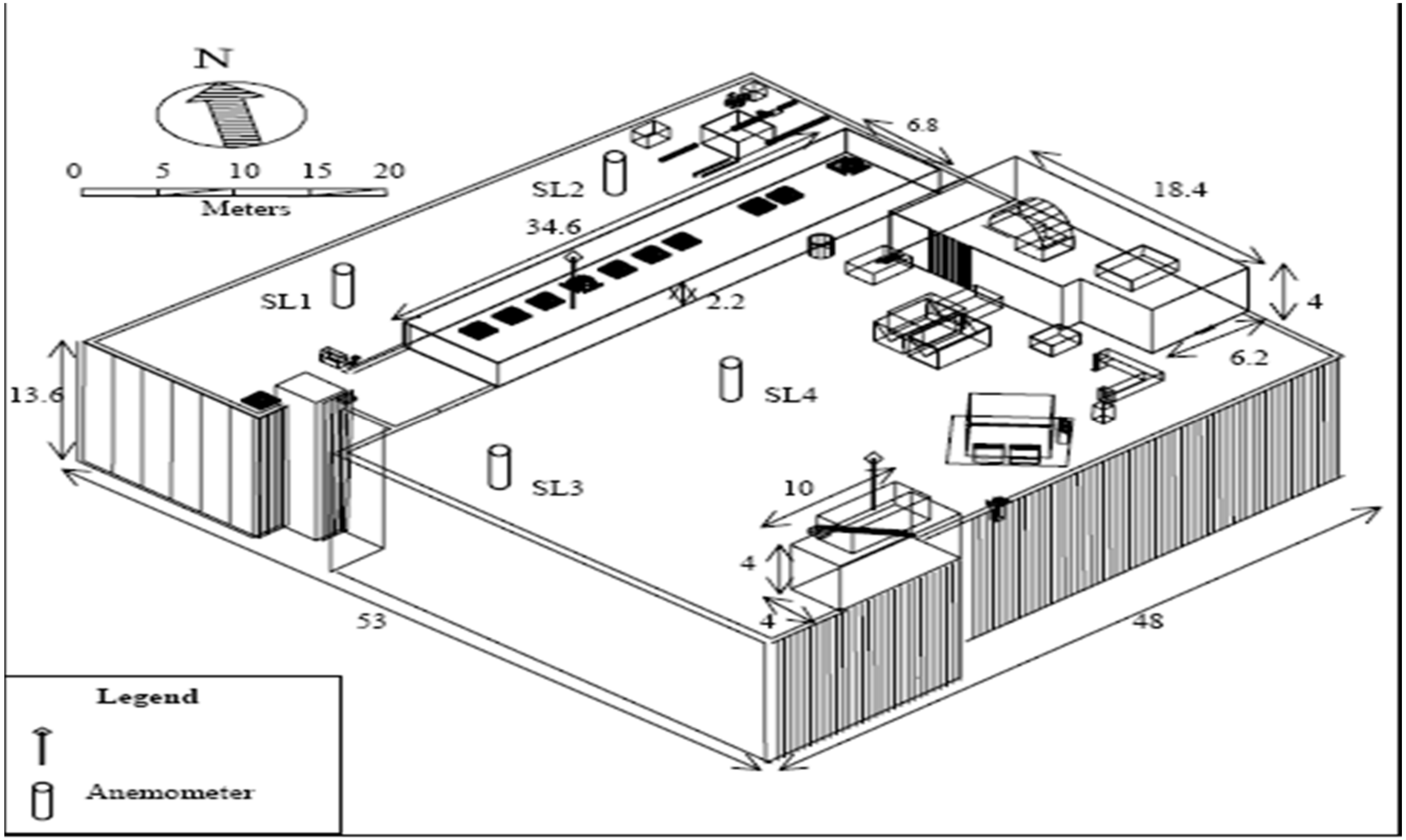

Normalised Dilution v/s Receptor Distance
M=5
Normalised Dilution
1000
100
10
1
0.1
0.01
0.001
3
5
10
15
20
25
30
Receptor Distance (m)
Wind Tunnel
ASHRAE 2003
ASHRAE 2007

Field Experiments

Field Experiments

- In Field Experiments the tests are done on existing buildings, data are real but they come too late to be used for design!
- Field Experiments are valuable to validate the experimental data and help improve simulation conditions and methodologies
- An Anemometer is used to estimate wind velocities and directions
- Tracer gas is released from a stack and air samples are collected at various receptors; concentrations are determined later by using suitable instrumentation

BE building, Concordia University, Montreal



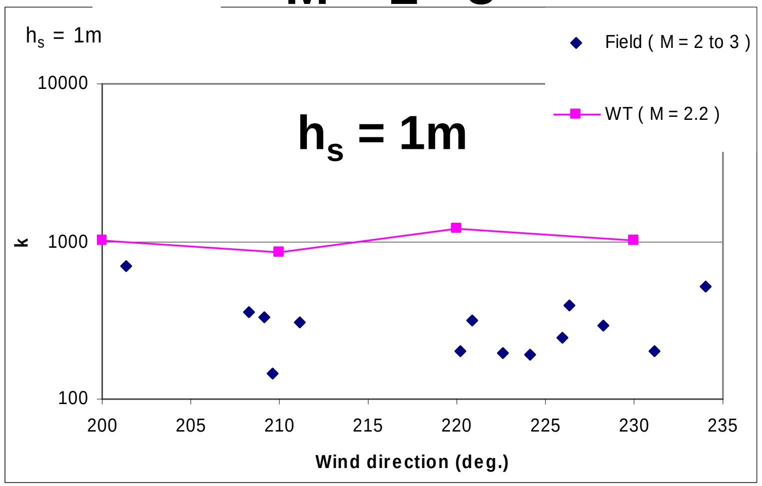
Detailed view of the BE building showing stack locations (SL), anemometers and various rooftop structures (dimensions in m)

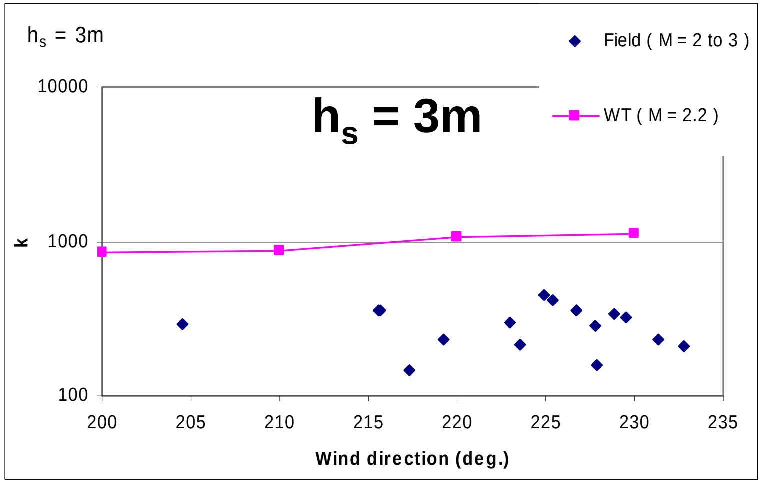
Photograph of the test stack used on the BE building (low stack with h_s=1m)

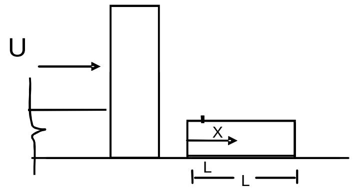
Photographs showing upwind terrain for the various field tests

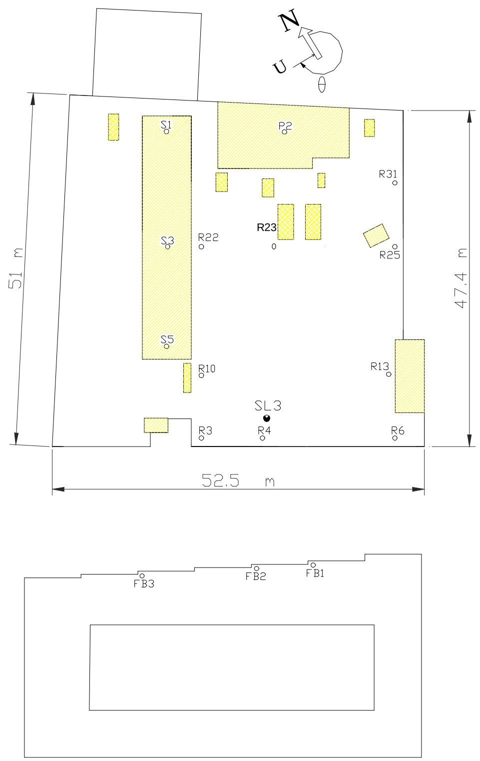
FG building upwind: Effect of wind direction on k (BE Bldg roof)

M = 2 - 3









Merits of Field Experiments

- Reliable results since measurements are carried out in actual conditions

- Absolutely necessary for validation purposes

Demerits of Field Experiments

- Expensive and dependent on proper weather conditions

- Difficult to carry out; instrumentation and equipment problems

- Being weather dependent, field tests are time consuming

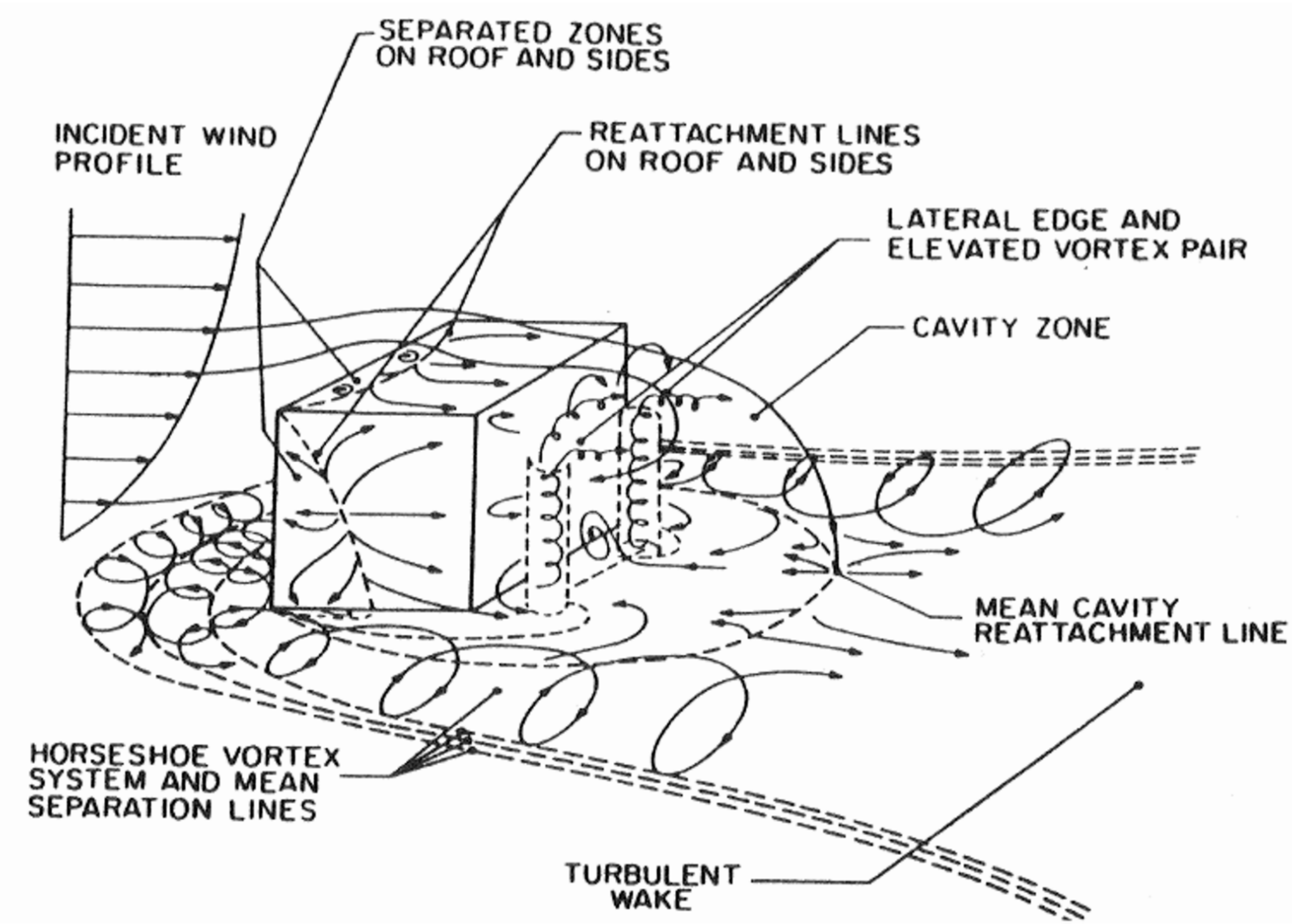
Numerical Techniques

Numerical Techniques

- Numerical techniques are used to solve the basic equations in Fluid Mechanics (Navier-Stokes Equations)
- Solutions are iterative in nature and have to satisfy certain convergence conditions
- This can be done by special computer programs or by using commercially available CFD software (such as FLUENT)
- Application of CFD is complex and far from being successful in several cases

Flow Around an Isolated Sharp-Edged Building

Knowledge well established in Wind Engineering Community

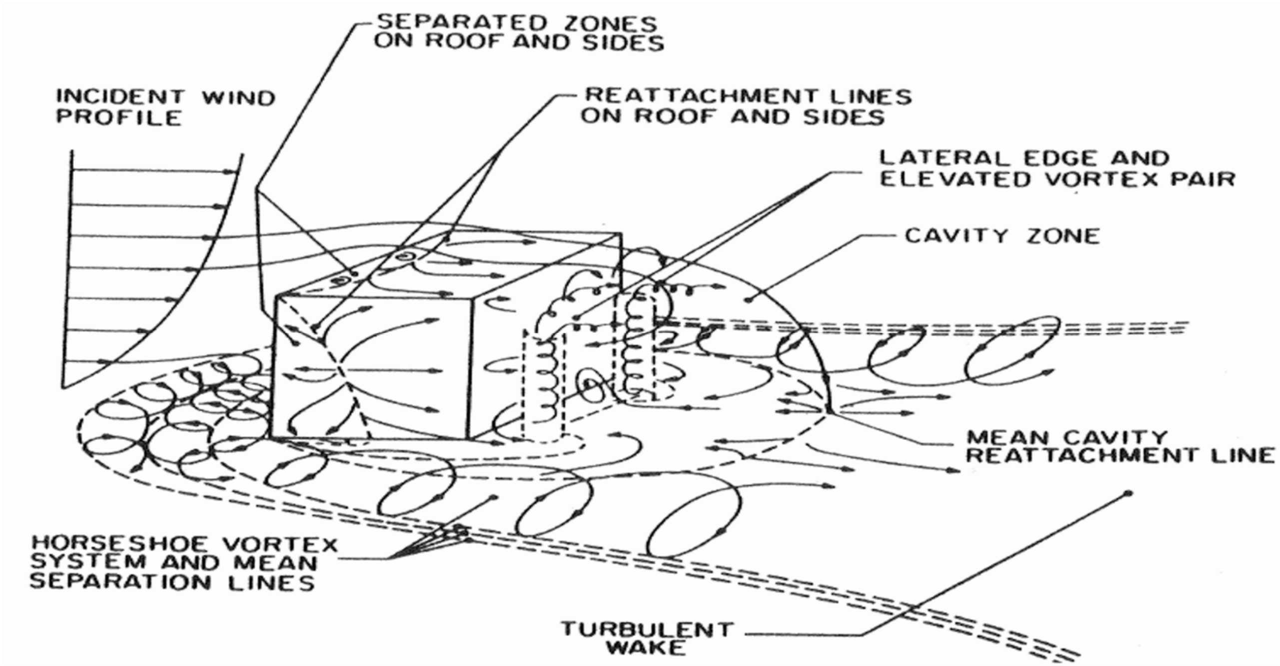


(from Hosker 1984, based on Woo et al. 1977 and Hunt et al. 1978)

Pollutants Released at or Above the Roof or Sides

Different scenarios can occur, depending on:

a) release inside or outside the separation bubble
b) reattachment on roof/sides or not
c) release momentum ratio is sufficient or not to escape the separation bubble.



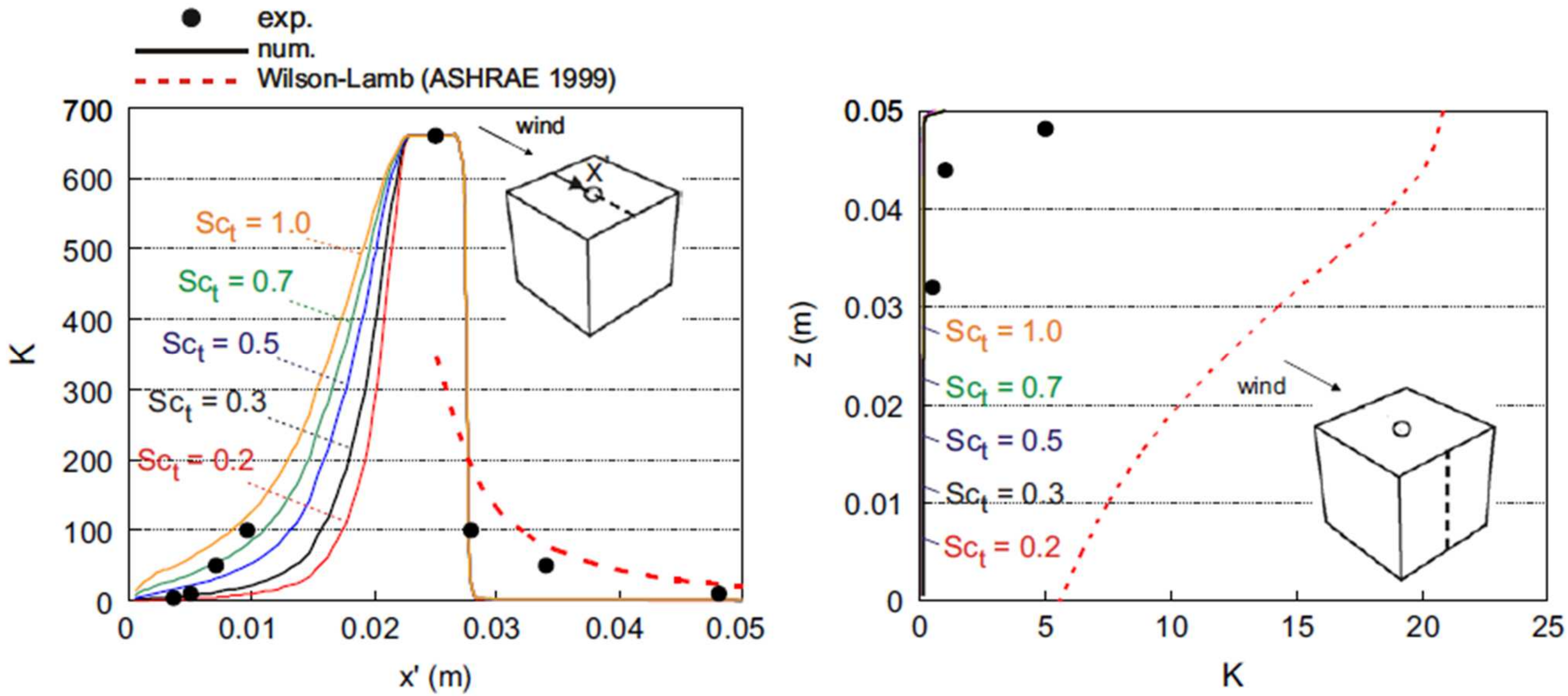
(from Hosker 1984, based on Woo et al. 1977 and Hunt et al. 1978)

CFD Turbulence Models

- Direct Numerical Simulation
- RANS
- k-ε model and variations
- Large Eddy Simulation model

- Stathopoulos et al (2008) have applied “Steady-state RANS” through CFD to simulate pollutant dispersion using FLUENT for isolated building and effects of rooftop structures.

- Comparison of these results were made with ASHRAE and wind tunnel experiments



From Blocken et al. 2008

Merits of CFD Modelling

- Low cost involved since it requires only a computer and any commercially available CFD code (such as FLUENT)

- The time required for computation is less compared to wind tunnel or field experiments

Demerits of CFD Modelling

- Validation of CFD models is a crucial prerequisite for practical applications
- For complex building geometries and configurations CFD may not give satisfactory results
- Accuracy of the results depends on the actual modelling problem (structural vs environmental applications)

EPA Approved Dispersion Models

Environmental Protection Agency

- Responsible for enforcing laws for protecting the Environment

- Dispersion models are categorized as:
  - **Preferred/Recommended Models** (e.g: CALPUFF)
  - **Alternative Models** (e.g: ADMS, AFTOX)
  - **Screening Tools** (e.g: SCREEN 3)

Dispersion Models Require the Following Inputs:

- Meteorological conditions such as wind speed and direction, the amount of atmospheric turbulence and ambient air temperature
- Emission parameters such as source location and height, stack diameter and exit velocity, effluent temperature and mass flow rate
- Terrain elevations at the source and receptor location
- The location, height and width of any obstructions (such as buildings or other structures) in the path of the emitted gaseous plume

CALPUFF

- A non-steady-state dispersion model that simulates effects of time- and space-varying meteorological conditions on pollution transport.
- CALPUFF can be applied for long-range transport and complex terrain.
- The main components of the package are:
- CALMET (a 3-D pre-processor meteorological model)
- CALPUFF (an air quality dispersion model)
- CALPOST (a post processing package)

ADMS 3

- Atmospheric Dispersion Modeling System (ADMS 3) is an advanced dispersion model developed in England

- Used for calculating concentration of pollutants emitted both continuously/discretely from point, line, volume and area sources

- Outputs can be given as contour plot/concentrations at specific locations

- Several validation studies for ADMS have been carried out for pollutant dispersion in urban environment (Britter et al, 2007)

AFTOX

- AFTOX (Air Force Toxic Chemical Dispersion Model) is a Gaussian dispersion model that handles continuous or instantaneous liquid or gas elevated or surface releases from point or area sources

- Output consists of concentration contour plots, mean and maximum concentration at a specified location, at a given elevation and time

SCREEN 3

- SCREEN 3 is a single source Gaussian plume model
- It provides maximum ground-level concentrations for point, area, flare and volume sources
- It also gives concentrations in cavity zones, as well as concentrations due to inversion break-up and shoreline fumigation
- SCREEN 3 is a screening version of the Industrial Source Complex ISC 3 model

Merits of EPA Models

- Some of these models such as ADMS and CALPUFF can model building and stack downwash effects

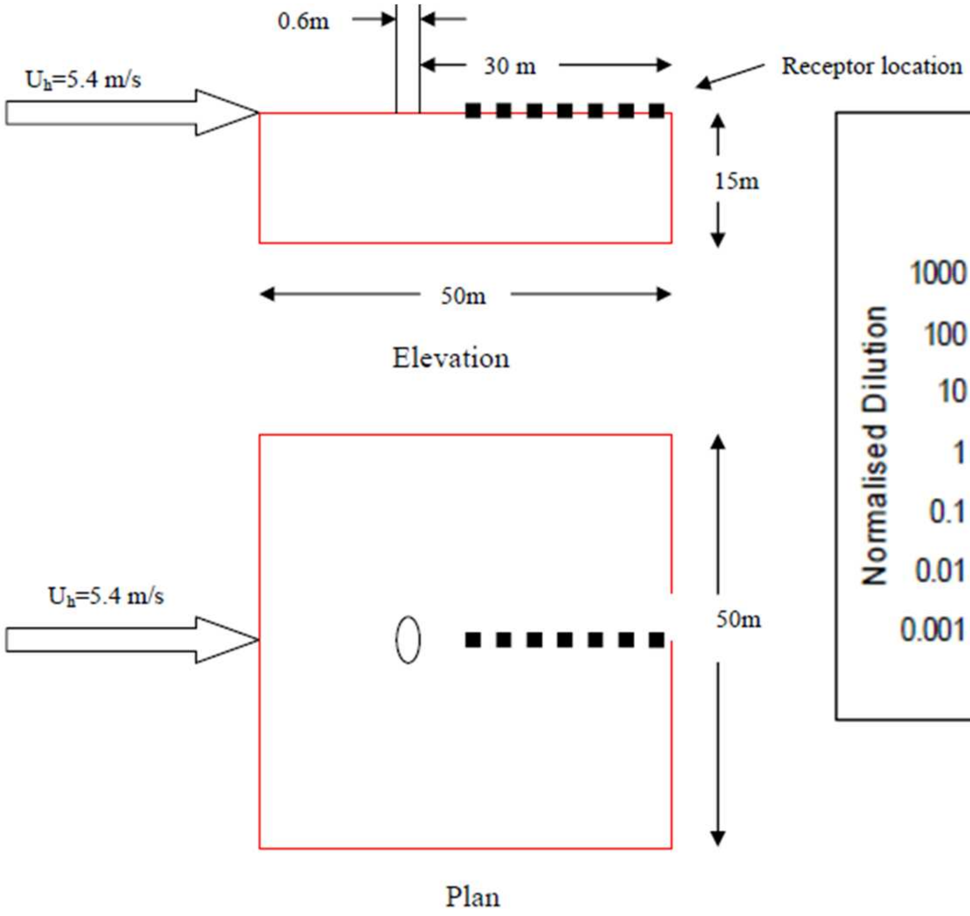
- These models can save time and money when compared to field and wind tunnel experiments, as well as CFD calculations

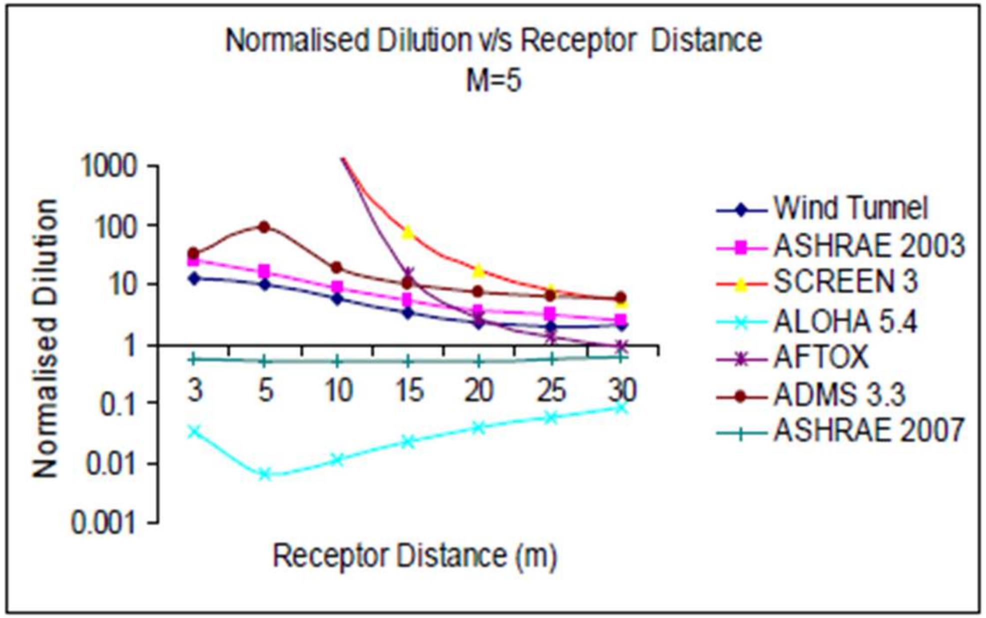
- Versions of these models can be downloaded freely from the web

Demerits of EPA Models

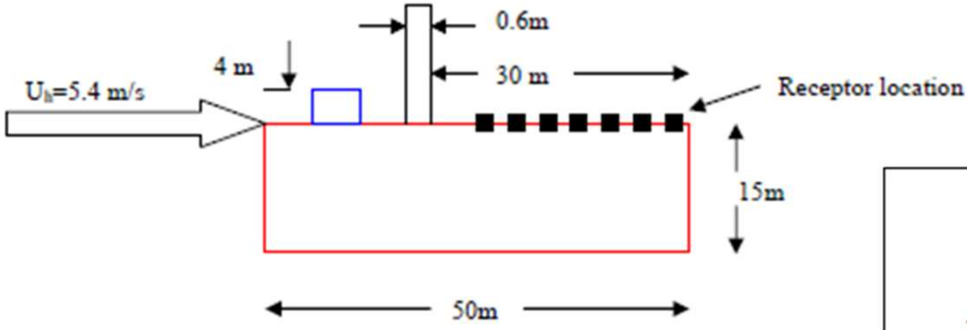
- Most models (except ADMS) predict very high concentrations within the first 10m from stack; hence unsuitable for near-field dispersion problems
- Most models are suitable for isolated stacks and do not take into account building and stack downwash effects
- The effect of change in wind direction cannot be modelled by these models (except ADMS)
- The effect of rooftop structures and other architectural details cannot be modelled by these EPA models

Case Study

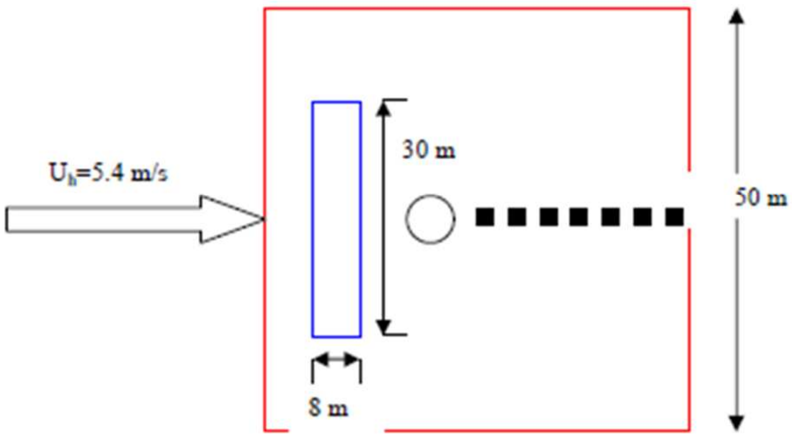




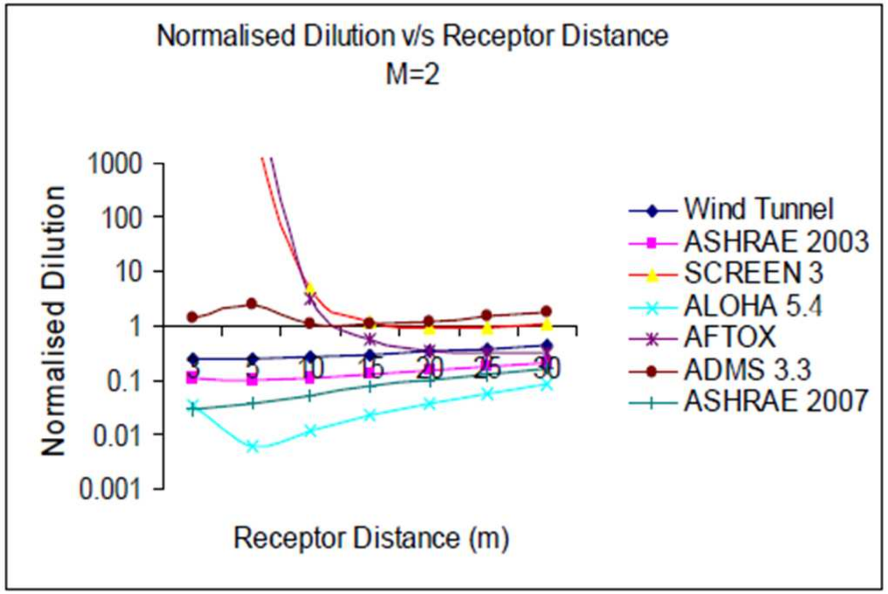
Stathopoulos et al. 2008



Elevation



Plan



IRSST and collaborative research program with Concordia University

IRSST

- Established in Québec in 1980, the *Institut de recherche Robert-Sauvé en santé et en sécurité du travail* (IRSST) is a scientific research organization known for the quality of its work and the expertise of its personnel.

- Scientific activities are concentrated within the occupational health and safety network and the working community.

- Collaborative projects involving research in dispersion have been conducted jointly by Concordia University and IRSST

- Details can be obtained from: www.irsst.qc.ca

The personnel involved in these projects include:

Dr. T. Stathopoulos, Concordia

Dr. P. Saathoff

Dr. A. Gupta

Mr. B. Hajra - Graduate student, Concordia

Mr. M. Chavez – Graduate student, Concordia

Mr. L. Lazure - IRSST

Dr. A. Bahloul - IRSST

Design Guidelines

Codes and Standards

Quebec Law :

regulation respecting the quality of the work environment [S-2.1, r.15 (1994)] stipulates that fresh air intakes must be located so that no air already evacuated from an establishment is reintroduced.

- For laboratory fume hood exhausts, the American Industrial Hygiene Association (AIHA) *Standard* Z9.5 recommends a:

  - minimum stack height of 10 ft above the adjacent roof line; and extending one stack diameter above any architectural screen
  - minimum V_e of 3000 fpm; and

- The Uniform Plumbing Code (UPC) [IAPMO, 1997b] requires exhaust vents to be 3 ft or more above air inlets

- National Fire Protection Association (NFPA) *Standard* 45 specifies a minimum stack height of 10 ft to protect rooftop workers

- Petersen and Le Compte (2002) have suggested placing air intakes on building sidewalls

- The Uniform Mechanical Code (IAPMO 1997a), widely used in USA, recommends exhausts be at least 3 ft from property lines and 3 ft from openings into buildings

ASHRAE Guidelines

- The exhaust velocity (V_e) should be maintained above 2000 fpm (even with drains in the stack) to provide adequate plume rise and jet dilution. (ASHRAE 2003, Chapter 44)
- (V_e) should be at least 1.5 times the design wind speed U_H at roof height to avoid stack downwash (ASHRAE 2003, Chapter 44)
- Intakes near vehicle loading zones must be avoided, since these areas may have unacceptable waste

Additional Design Guidelines

- Stack location
  - Open fetch situation:
    - Stack should be placed near the center of roof (leading edge recirculation zone is avoided, thus, maximizing plume rise).
  - Taller building upstream:
    - Stack should be placed at the leading edge of roof (The roof level concentration decreases significantly but higher concentrations occur on the leeward wall of the adjacent building) - *Depends on distance between the buildings*

Additional Design Guidelines contd.

- Stack height
  - For x < 20 m
    - Increase in stack height from 1 m to 3 m reduced the roof level concentrations by a factor of 2.
    - To obtain significant (order of magnitude) reduction in concentration, a 7 m stack was required.
  - For x > 20 m
    - Increase in stack height from 1 m to 3 m had a negligible effect on roof level concentrations.
    - However, increase in stack height from 1 m to 5 m showed significant reduction on roof level concentrations.

x: linear distance from stack to inlet

Additional Design Guidelines contd.

- Exhaust Momentum
  - For x < 20 m
    - Increasing M by a factor of 2.5 decreases the concentration by the same factor.

Note: higher exhaust speed gives higher dilution due to:

- Larger plume rise
- Increased dilution at stack exit
- Increased entrainment of ambient air (initial dilution)

x: linear distance from stack to inlet

Additional Design Guidelines contd.

- Exhaust Momentum:

  - For $x > 20$ m

    - In the low M range ($1.5<M<4.5$), which is typical of wind speeds exceeding 5 m/s, increasing exhaust speed may not be beneficial for distant receptors because the plume rise may not be sufficient to avoid them

    - For light wind conditions, doubling the exhaust speed may cause M to be high enough so that concentrations are reduced over the entire roof.

x: linear distance from stack to inlet

Conclusions

- Wind Tunnel test results derived with correct simulation conditions are reliable, particularly when validated with field measurements.
- Field Experiments are costly and time consuming but indispensable for validation purposes
- CFD is an excellent tool for pollutant transport simulation in the urban environment, although requires further validation; at the moment is marginally successful
- The Semi-Empirical Models (ASHRAE) are questionable for the assessment of pollutant concentration in the vicinity of buildings; they may be suitable only for isolated buildings
- Most of the EPA models are not suitable to evaluate pollutant dispersion in the near-building environment
- Design guidelines useful to the profession started surfacing in the engineering practice

Thank you