西南交通大學
Southwest Jiaotong University

Chapter 20

Atmospheric Dispersion Modeling

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Preface

"Air pollution occurs when too much waste material is emitted into an air volume for the air's capacity to carry it away and dilute it. "

--- Explains the relation between air pollution and atmospheric dispersion

--- Dispersion is crucial for preventing high concentrations of pollutants

"Thus we must . . . understand atmospheric mechanisms that result in transport and dilution."

--- Explains the significance of understanding atmospheric dispersion mechanisms

20.1 Introduction

Background

Historical context of pollutant release into the atmosphere： implications

- **- As an old method of disposal**

  (tracing back to the discovery of fire and the use of chimneys to vent smoke）

- **- About the atmosphere's self-cleaning properties**

  (varied ability to disperse concentrated gaseous pollutants,

  based on local meteorological and geographical conditions.)

- **- Reliance on atmospheric dispersion for final disposal of pollutants**

  (despite advancements in pollution control measures, dispersion remains significant.)

20.1 Introduction

Importance and Necessity of Dispersion Modeling

—— Vital for predicting pollutant concentrations from new sources, a key component of air pollution engineering.

—— Allows for the prediction of impacts from future facilities, which cannot be measured directly.

—— A more cost-effective and practical approach compared to comprehensive measurement programs (Especially when dealing with multiple sources and the need to isolate individual source effects.)

—— Provides a consistent tool for assessment and comparison of different scenarios (precise and reproducible method), while not perfectly accurate.

Limitations of Dispersion Modeling

Limitations and Interpretation:

Dispersion models have limitations in accuracy.

* Important to use good judgment when interpreting results, especially for high-stakes policy decisions.

Complementing Modeling with Monitoring:

Actual ambient monitoring is crucial

- To provide real-world data for validating and adjusting/refining models.

(it balances the need for theoretical analysis with the realities of environmental conditions.)

-To ensure that policy decisions and industrial practices are based on a combination of theoretical predictions and empirical evidence.

20.2 A Physical Explanation of Dispersion

How does dispersion take place?

1.Simple molecular diffusion

Matter behaves “properly” by moving from a region of high concentration to one of lower concentration

2.Eddies in the atmosphere (from both thermal and mechanical influences)

Any fluid in turbulent flow contains eddies (or swirls)

Eddies can operate in both the lateral and vertical directions

3.Wind fluctuations

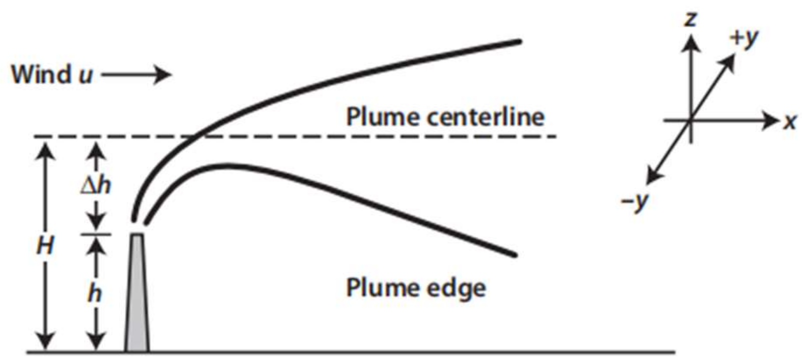

Figure 20.1
The spreading of a bent-over plume.

20.2 A Physical Explanation of Dispersion

Origin of Eddies

- **Thermal:** The thermal energy from the ground (absorbed from the sun) is transferred into the lowest levels of the air by conduction/convection, creating thermal eddies, and causing the air near the surface to rise.

- **Mechanical**: Surfaces with greater roughness (such as trees or buildings) create more eddies than smooth surfaces (ice or snow).

  A stronger wind produces more eddies.

20.2 A Physical Explanation of Dispersion

Plume broadened and diluted by the combined effect of many eddies of various sizes

Eddies + random shifting of the wind： **a time-averaged plume (spread)** rather than an instantaneous basis.

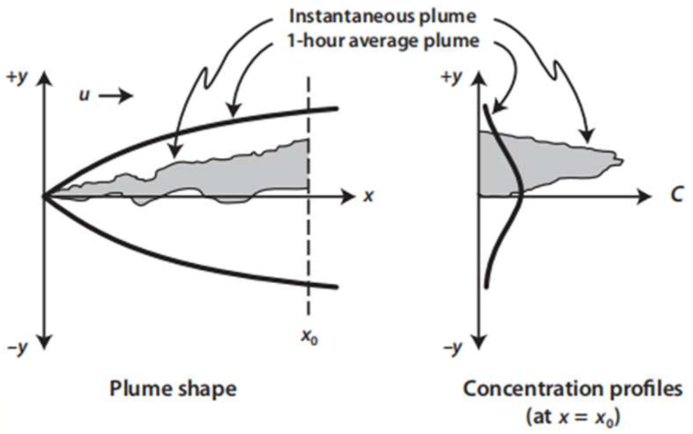

Figure 20.2
Top view of an instantaneous plume and a 1-hr average plume and their corresponding concentration profiles.

20.2 A Physical Explanation of Dispersion

The binormal distribution of pollutant:

A spreading of the plume occurs in both the vertical and horizontal directions, resulting in normal distribution of pollutant concentration in both directions.

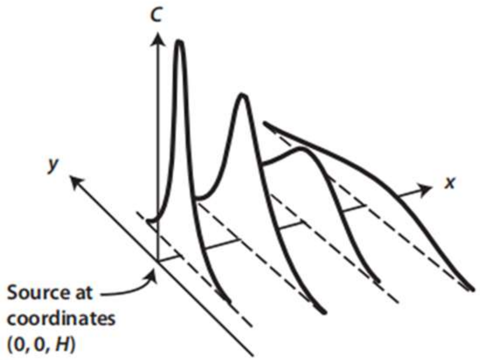

Figure 20.3
Behavior of the downwind, elevated transverse concentration profiles as a function of distance downward.

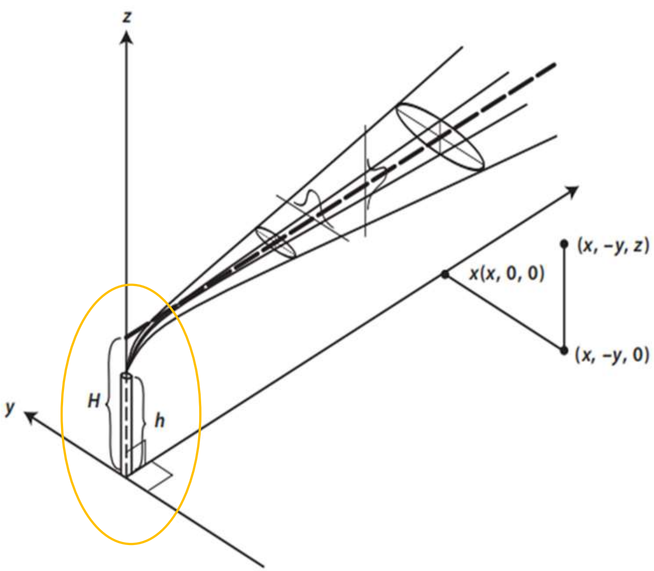

Figure 20.4
Coordinate system showing Gaussian distributions in the horizontal and vertical.
(Adapted from Turner, 1970.)

20.2 A Physical Explanation of Dispersion

Developing an equation to model this behavior:

Approach 1 (approximate physical reality)

To model the wind as being absolutely constant and accounting for the plume spread by eddy diffusivities alone.

A second-order partial differential equation can be derived from material balance considerations.

One particular solution to this equation is known as the Fickian diffusion equation, which predicts the pollutant concentration to be binormally_distributed.

Approach 2 (more valid)

Based on the statistical nature of the dispersion process.

This model is usually referred to as the Gaussian dispersion equation

20.3 The Gaussian Model 655

The Gaussian dispersion equation is extremely important in air pollution work.

It is the basis for almost all of the computer programs developed by the U.S. EPA for atmospheric dispersion modeling.

How to use of the Gaussian equation:

- Illustrations
- Estimating the Maximum Downwind Ground-Level Concentration

20.3 The Gaussian Model

Main Assumptions

1. **Gaussian Distribution of Concentrations:**

The concentration of pollutants disperses in a normal (Gaussian) distribution pattern in the crosswind and vertical directions.

2. **Uniform Wind Field:**

The wind speed and direction are constant and uniform over the area of interest, which simplifies the advection of the pollutant plume.

3. **Steady-State Conditions:**

The release of pollutants and the meteorological conditions are constant over time, which allows for the use of time-averaged concentrations.

4. **No Chemical Reactions:**

not account for chemical reactions or transformations of the pollutants during transport.

Why make assumptions for the Gaussian model?

-to simplify the complex processes involved in atmospheric dispersion.

-to provide relatively simple and computationally efficient predictions of pollutant dispersion.

Disadvantage from the assumptions

-introduce limitations to the model's accuracy, particularly

in complex terrains,

under variable meteorological conditions,

when dealing with non-steady-state emissions.

20.3 The Gaussian Model

Gaussian models/ Gaussian plume models:

widely used for predicting the dispersion of pollutants in the atmosphere.

*plume: the contaminated stream

A brief review of Gaussian or normal distribution:

often results from random processes.

Appendix C: Some Properties of a Gaussian Distribution: Page 786

A probability density function (pdf) ~ A continuous random variable

μ = the mean of x

σ = the standard deviation of x

- standard normal distribution function
- normalized or standard Gaussian distribution

*pay attention to the extra σ

20.3 The Gaussian Model   655

The time-averaged concentration profiles (binormal) about a plume centerline :

well modeled by a double Gaussian equation by Pasquill (1961).

$$C = \frac{Q}{2\pi u \sigma_y \sigma_z} \exp\left(-\frac{1}{2}\frac{y^2}{\sigma_y^2}\right)\left\{\exp\left(-\frac{1}{2}\frac{(z-H)^2}{\sigma_z^2}\right) + \exp\left(-\frac{1}{2}\frac{(z+H)^2}{\sigma_z^2}\right)\right\} \tag{20.1}$$

Prediction of steady-state concentration at a point (x, y, z) located downwind from a nonreactive gaseous pollutant from an elevated source

where

C = steady-state concentration at a point (x, y, z), µg/m^3

Q = emissions rate, µg/s

σ_y, σ_z = horizontal and vertical spread parameters, m (these are functions of distance, x, and atmospheric stability)

u = average wind speed at stack height, m/s

y = horizontal distance from plume centerline, m

z = vertical distance from ground level, m

H = effective stack height ($H = h + \Delta h$, where h = physical stack height and Δh = plume rise, m)

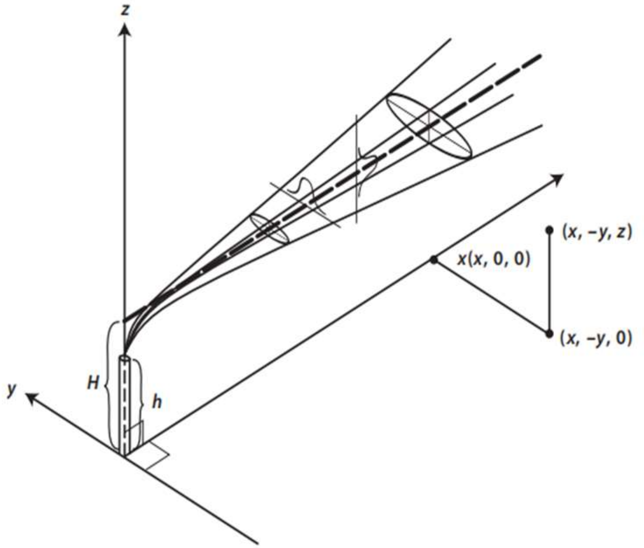

Figure 20.4
Coordinate system showing Gaussian distributions in the horizontal and vertical.
(Adapted from Turner, 1970.)

20.3 The Gaussian Model

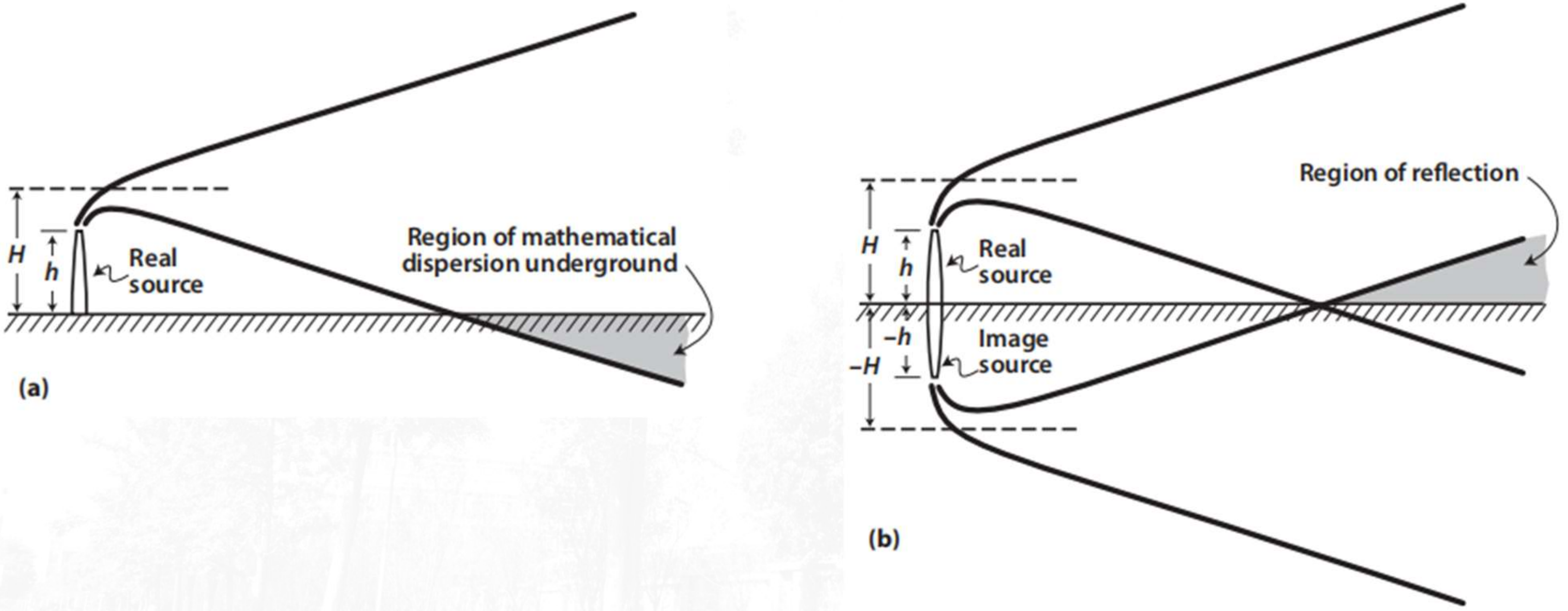

Figure 20.5
Schematic diagram depicting (a) mathematical dispersion of pollutants underground and (b) reflection due to an "image source."

20.3 The Gaussian Model

The accumulation of pollutants/concentration is influenced by

- emission rates
- dispersion rates
- chemical reactions.

Dispersion is heavily dependent on

- local meteorological conditions
  - wind
  - atmospheric stability

A brief discussion of wind / atmospheric stability estimation

20.3 The Gaussian Model

In Chapter 19, we introduced the power law to predict the variation of wind speed with height. The equation is repeated below for convenience:

$$\frac{u_2}{u_1} = \left(\frac{z_2}{z_1}\right)^p \tag{19.1}$$

where

z_1, z_2 = elevations 1 and 2

u_1, u_2 = windspeeds at z_1 and z_2

p = exponent

Table 20.3 Exponents for Wind Profile (Power Law) Model

	Exponent (p)	
Stability Class	**Rough Surface (urban)**	**Smooth Surface (rural)**
A	0.15	0.07
B	0.15	0.07
C	0.20	0.10
D	0.25	0.15
E	0.30	0.35
F	0.30	0.35

Adapted from U.S. Environmental Protection Agency, 1995.

20.3 The Gaussian Model-Atmospheric Stability Classes

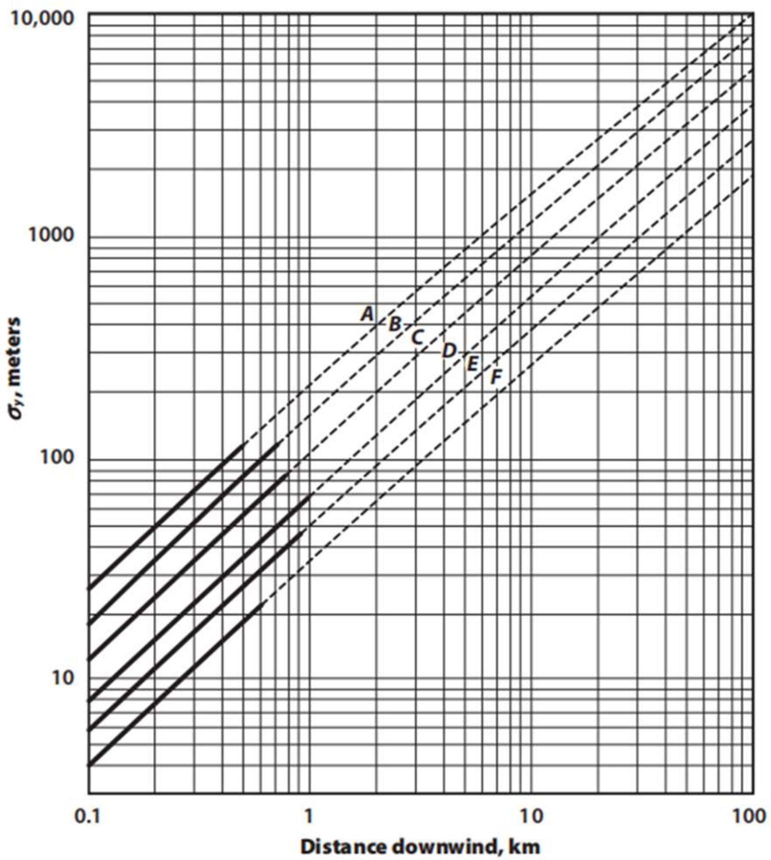

Figure 20.7
Horizontal dispersion coefficient as a function of downwind distance from the source.
(Adapted from Turner, 1970.)

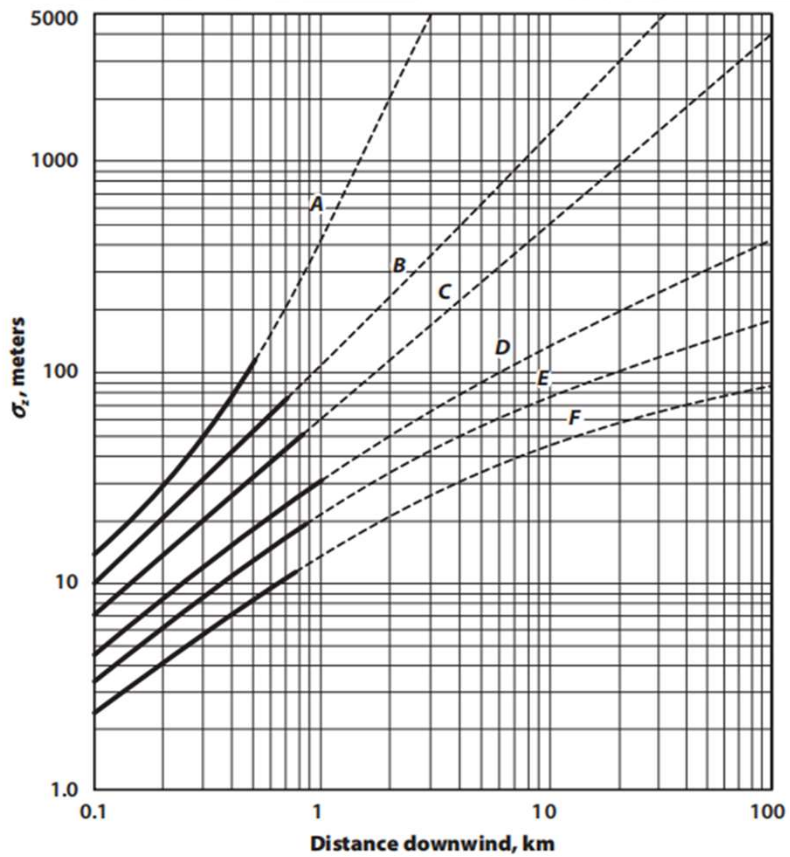

Figure 20.8
Vertical dispersion coefficient as a function of downwind distance from the source.
(Adapted from Turner, 1970.)

A brief discussion of atmospheric stability estimation

20.3 The Gaussian Model-Atmospheric Stability Classes

Table 20.1 Stability Classifications*

Surface Wind Speed[a] m/s	Day Incoming Solar Radiation: Strong[b]	Day Incoming Solar Radiation: Moderate[c]	Day Incoming Solar Radiation: Slight[d]	Night Cloudiness[e]: Cloudy (≥4/8)	Night Cloudiness[e]: Clear (≤3/8)
<2	A	A–B[f]	B	E	F
2–3	A–B	B	C	E	F
3–5	B	B–C	C	D	E
5–6	C	C–D	D	D	D
>6	C	D	D	D	D

[a] Surface wind speed is measured at 10 m above the ground.
[b] Corresponds to clear summer day with sun higher than 60° above the horizon.
[c] Corresponds to a summer day with a few broken clouds, or a clear day with sun 35-60° above the horizon.
[d] Corresponds to a fall afternoon, or a cloudy summer day, or clear summer day with the sun 15–35°.
[e] Cloudiness is defined as the fraction of sky covered by clouds.
[f] For A–B, B–C, or C–D conditions, average the values obtained for each.

* A = Very unstable   D = Neutral
B = Moderately unstable   E = Slightly stable
C = Slightly unstable   F = Stable
Regardless of wind speed, Class D should be assumed for overcast conditions, day or night.

Adapted from Turner, 1970.

20.3 The Gaussian Model-Atmospheric Stability Classes

- Often it is difficult to obtain consistent readings from Figures 20.7 and 20.8.
- Such graphical representations are inconvenient for use in computer programs.

Martin (1976) published equations that give reasonable fits to these curves.

$$\sigma_y = ax^b \tag{20.3}$$

and

$$\sigma_z = cx^d + f \tag{20.4}$$

where a, b, c, d, and f are constants that are dependent on the stability class and on the distance x (x must be expressed in km).

Table 20.2 Values of Curve-Fit Constants for Calculating Dispersion Coefficients as a Function of Downwind Distance and Atmospheric Stability

			$x < 1$ km			$x > 1$ km		
Stability	***a***	***b***	***c***	***d***	***f***	***c***	***d***	***f***
A	213	0.894	440.8	1.941	9.27	459.7	2.094	–9.6
B	156	0.894	106.6	1.149	3.3	108.2	1.098	2.0
C	104	0.894	61.0	0.911	0	61.0	0.911	0
D	68	0.894	33.2	0.725	–1.7	44.5	0.516	–13.0
E	50.5	0.894	22.8	0.678	–1.3	55.4	0.305	–34.0
F	34	0.894	14.35	0.740	–0.35	62.6	0.180	–48.6

Adapted from Martin, 1976.

Example 20.1

Nitric oxide (NO) is emitted at 110 g/s from a stack with physical height of 80 m. The wind speed at 80 m is 5 m/s on an overcast morning. Plume rise is 20 m.

(a) Calculate the ground-level centerline concentration 2.0 km downwind from the stack.

(b) Calculate the concentration at 100 m off the centerline at the same x distance.

Example 20.2

Consider the same data as in Example 20.1, except that the meteorology is such that the wind speed (at 10 m) is 4 m/s and it is midafternoon on a hot summer day.

Calculate the ground-level centerline concentration at x = 2.0 km, assuming rough terrain

The Dependence of Concentration on Averaging Time 665

$$C_t = C_{10}\left(\frac{10}{t}\right)^{0.5} \quad \textbf{(20.5)}$$

where

t = averaging time, min

C_t = concentration for averaging time t

20.3 The Gaussian Model

Estimating the Maximum Downwind Ground-Level Concentration

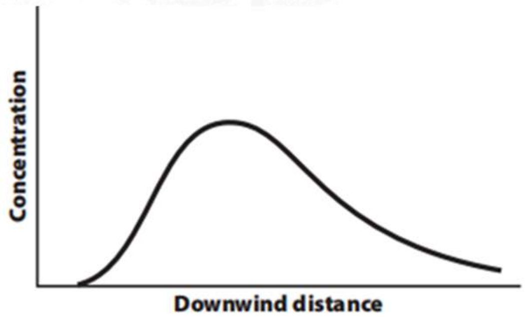

Figure 20.6
Variation of ground-level centerline concentrations with distance down-wind from an elevated source.

$$C = \frac{Q}{\pi u \sigma_y \sigma_z} \exp\left(-\frac{H^2}{2\sigma_z^2}\right) \qquad (20.11)$$

20.3 The Gaussian Model

Estimating the Maximum Downwind Ground-Level Concentration

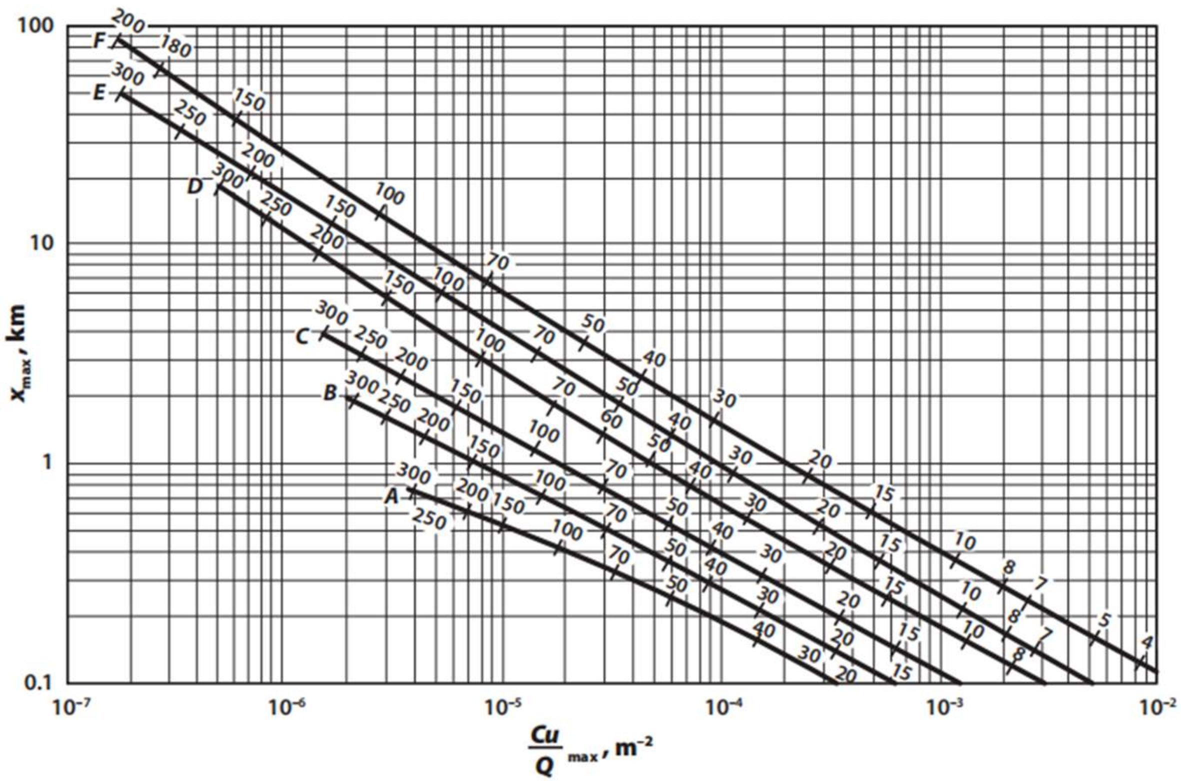

Figure 20.9
Maximum (Cu/Q) and distance to C_{max} as a function of stability (solid lines) and effective stack height (numbers [in meters]).(Adapted from Turner, 1970.)

Turner (1970) : a graphical means of estimating C_{max} and x_{max}
~ stability class, effective stack height, wind speed, and emission rate.

If one knows the stability class, the effective height, the wind speed, and the emission rate. one may calculate Cmax and x max.

20.3 The Gaussian Model-Atmospheric Stability Classes

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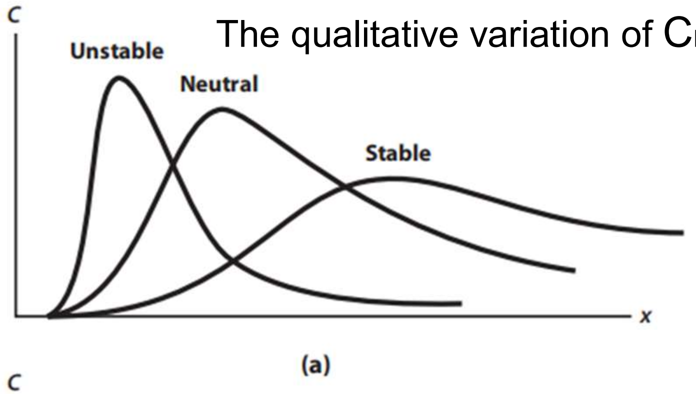
Estimating the Maximum Downwind Ground-Level Concentration 666

The qualitative variation of C_{max} and x_{max} with stability



The qualitative variation of C_{max} and x_{max} with H

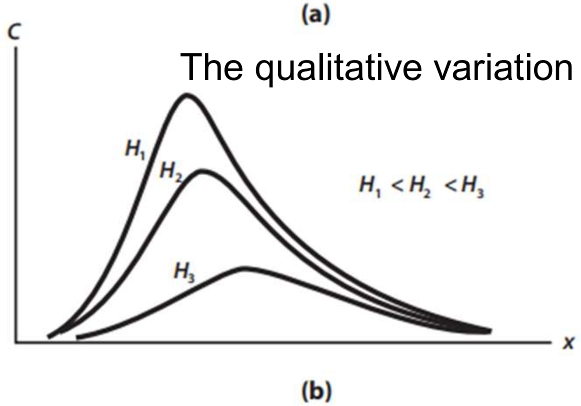


Figure 20.10
Behavior of ground-level centerline concentration from an elevated source as a function of downwind distance and (a) atmospheric stability (at constant *H*), and (b) effective stack height (at constant stability).

Table 20.4 Values of Curve-Fit Constants for Estimating $(Cu/Q)_{max}$ from *H* as a Function of Atmospheric Stability

	Constants			
Stability	***a***	***b***	***c***	***d***
A	−1.0563	−2.7153	0.1261	0
B	−1.8060	−2.1912	0.0389	0
C	−1.9748	−1.9980	0	0
D	−2.5302	−1.5610	−0.0934	0
E	−1.4496	−2.5910	0.2181	−0.0343
F	−1.0488	−3.2252	0.4977	−0.0765

Adapted from Ranchoux, 1976.

Estimating the Maximum Downwind Ground-Level Concentration

Example 20.3

Given the same data as Example 20.1, estimate the maximum ground-level concentration and the distance at which it occurs

20.3 The Gaussian Model

Estimating the Downwind Concentration under an Elevated Inversion 669

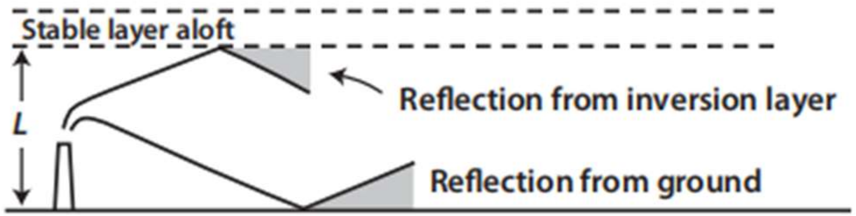


Figure 20.11
Plume dispersion under an elevated inversion.

$$C = \frac{Q}{2\pi u \sigma_y \sigma_z}\left[\exp\left(\frac{-1}{2}\frac{y^2}{\sigma_y^2}\right)\right]\sum_{-\infty}^{+\infty}\left\{\exp\left(\frac{-(z-H+2jL)^2}{2\sigma_z^2}\right) + \exp\left(\frac{-(z+H+2jL)^2}{2\sigma_z^2}\right)\right\} \quad (20.7)$$

where L = height from the ground to the bottom of the inversion layer, m. In practice, it is only necessary to vary the summation index, j, from -2 to $+2$ to obtain reasonable convergence of Eq. (20.7).

$$C = \frac{Q}{(2\pi)^{1/2} u \sigma_y H}\exp\left(-\frac{1}{2}\frac{y^2}{\sigma_y^2}\right) \quad (20.8)$$

$$\sigma_z = 0.47(L-H) \quad (20.9)$$

$$C = C_i + \frac{\Sigma Q_j}{uHW} \tag{20.10}$$

where

C = concentration of a conservative pollutant in the air leaving the box, μg/m^3

C_i = concentration of that pollutant in the air coming into the box, μg/m^3

Q_j = emissions of that pollutant from the j^{th} source within the box, μg/s

u = wind speed, m/s

H = height of the box, m

W = width of box, m

20.4 Tall Stacks and Plume Rise 671

Design Procedures

1. Analyze the meteorology.
2. Make a preliminary hazard assessment based on meteorology.
3. Test various cases of physical stack parameters (height and diameter), plume rise models, and plant locations in conjunction with the "worst-case" meteorology.
4. Consider effects of local terrain.
5. Review your results—do they make sense?

Table 20.5 Heights of Tall Things

Stacks	ft	Buildings	ft
Inco Smelter (Subdury, Ontario)	1250	Burj Khalifa (Dubai)	2720
Am. Electric Power Mitchell Plant	1206	CN Tower (Toronto)	1815
TVA-Cumberland Plant	1000	Empire State Building	1250
TVA-Paradise Plant	800	Eiffel Tower	984
TVA-Gallatin Plant	500	Washington Monument	555

Adapted from Schnelle, 1976.

Table 20.6 The Inco Copper Smelter Stack, Sudbury, Ontario

Height	1250 ft
Diameter at top and at base	52 ft (top), 116 ft (base)
Inside diameter at top	50 ft
Stack gas velocity	65–70 ft/sec

Adapted from Schnelle, 1976.

20.4 Plume Rise

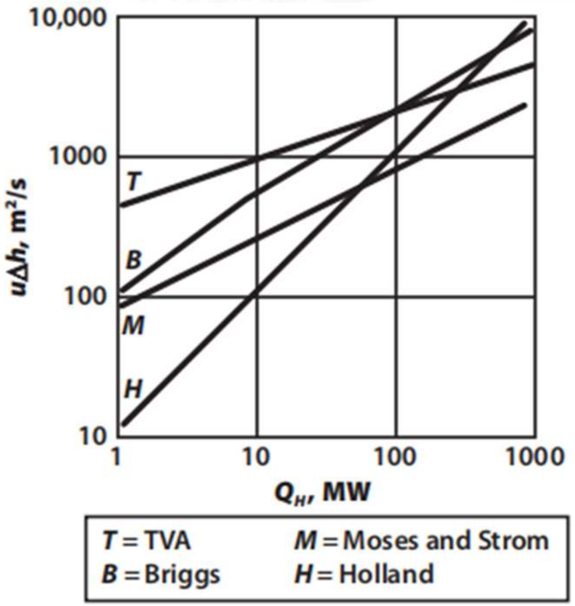


Figure 20.13
Comparisons of various plume rise models.
(Adapted from Briggs, 1975.)

how to calculate： example 20.6

The physical stack height is a completely free design parameter, but the plume rise is very important and can be larger than the physical stack height in some cases.

Failure to account for the beneficial effects of plume rise might result in excessive overdesign of the stack and a considerable unnecessary expense.

$$\Delta h = \frac{v_s d_s}{u}\left[1.5 + 2.68(10)^{-3} P_a \left(\frac{T_s - T_a}{T_s}\right) d_s\right] \qquad \textbf{(20.12)}$$

where

v_s = stack gas velocity, m/s
u = mean wind speed at stack height, m/s
d_s = stack inner diameter, m
P_a = atmospheric pressure, mb
T_s = stack gas temperature, K
T_a = atmospheric temperature, K

20.4 Tall Stacks and Plume Rise

Critical Wind Speed 679

C_{max} at x_{max}:

$$C = \frac{Q}{\pi u \sigma_y \sigma_z} \exp\left(-\frac{H^2}{2\sigma_z^2}\right) \quad (20.11)$$

u_{10}, m/s	u_h, m/s	C_{max}, μg/m³	x_{max}, km	H, m
1.0	1.4	10.3	48	512
2.0	2.8	20.3	18.5	306
3.0	4.2	26.5	11.7	237
4.0	5.6	29.9	8.9	203
5.0	6.9	31.5	7.4	182
6.0	8.3	32.1	6.5	169
7.0	9.7	32.1	5.9	159
8.0	11.1	31.7	5.4	152
10.0	13.9	30.3	4.8	141

u ↑
the pre-exponential term ↓
the exponential term ↑

a maximum Cmax exists at some wind speed, u_c, called the critical wind speed (depends on the stability and the specific plume rise model used)

20.4 Other Stack Design Considerations 680

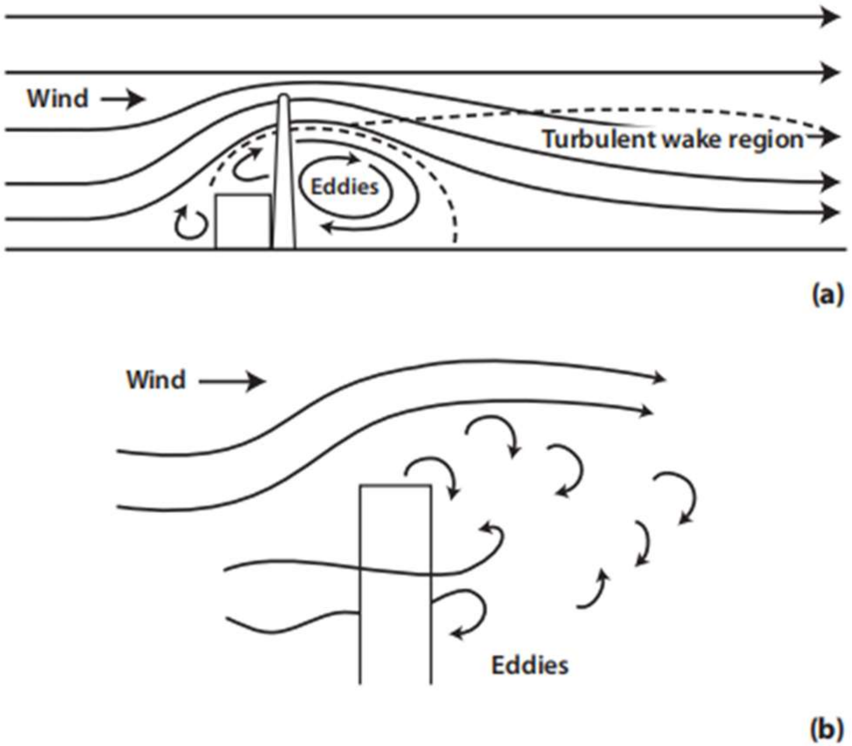


Figure 20.14
Typical flow disturbances owing to (a) a building and (b) a stack.

Figure 20.15
A view of a large power plant showing the wind turning vanes on the six steel stacks. Note the electrostatic precipitator on the far left of the photograph.

These effects may result in plume downwash unless the designer takes steps to compensate for them.

20.4 Stack Costs 682

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For cost-estimating purposes, stacks are classified as:

short (< 120 feet) or tall (>1000 feet)

Short stack : a vertical duct supported in some manner (by its own structure, by an external structure, or with guy wires). (steel, brick, or FRP)

Tall stack: free-standing, but more attention to the structural aspects of design (must be strong enough to stand against strong wind loadings)

Other components of tall stacks :

strong foundations, ladders, sampling platforms, access doors, and even aircraft warning lights.

Tall stacks are quite a bit bigger at the base than at the top

The costs of short stacks depend primarily on three factors:

stack height, stack diameter, and material of construction

$$C = aH^b \tag{20.24}$$

Table 20.7 Cost Estimating Parameters for Short Stacks

	Equation Parameter*		Applicable Range	
Material	**a**	**b**	***D*, in.**	***H*, feet**
PVC[1]	0.393	1.61	12–36	≤ 10
Plate – CS, coated[2]	3.74	1.16	6–84	20–100
Plate – 304 SS[3]	12.0	1.20	6–84	20–100
Sheet – Galv CS[4]	2.41	1.15	8–36	< 75
Sheet – 304 SS[5]	4.90	1.18	8–36	< 75

* For use with Equation 20.23
[1] polyvinyl chloride
[2] carbon steel plate, coated with one coat of shop paint
[3] stainless steel plate, type 304
[4] carbon steel sheet, galvanized
[5] stainless steel sheet, type 304

Adapted from Vatavuk, 1996.

20.5 Computer Programs for Dispersion Modeling (Point Sources) 684

The most widely used today are the Gaussian-based models.

Advantages:

(1) easy to understand and apply,

(2) the mathematics are relatively simple and easily adaptable to computer programs.

Limitations: The dispersion parameters were determined empirically over only a limited range of conditions and the Gaussian approach is far from perfect.

Various modifications of the basic Gaussian equation have been made to account for such things as elevated inversions, line or area sources, and topography.

(a refined point source Gaussian air quality model, a refined version)

(considering all stability conditions for relatively uncomplicated or complex terrain)

Be aware of the assumptions and limitations built into the program you are using, and do not use it to try to solve problems for which it was never designed.

EPA models: listed by name in Appendix D

20.5 Computer Programs for Dispersion Modeling (Point Sources)

All of the programs are written in FORTRAN,
all use the Briggs plume rise equation, and
all require various sorts of meteorological data.

The preferred/recommended models are those typically used (and accepted automatically by EPA) in modeling for regulatory purposes (permits, impact assessments, and other actions taken to legally comply with state or federal regulations).

Screening models are used for quick evaluations to estimate the maximum impacts that may occur from a facility. (very useful for screening studies; often accepted by agencies)

Alternative models are used for special cases, such as a spill and escape of a toxic gas. (used and accepted by regulatory agencies on a case-by-case basis)

The accuracy of Gaussian plume models can be improved by refining the assumptions and incorporating more detailed representations of atmospheric processes, as seen in models like AERMOD, which uses a probability density function approach to account for non-Gaussian distributions of vertical velocities in the convective boundary layer

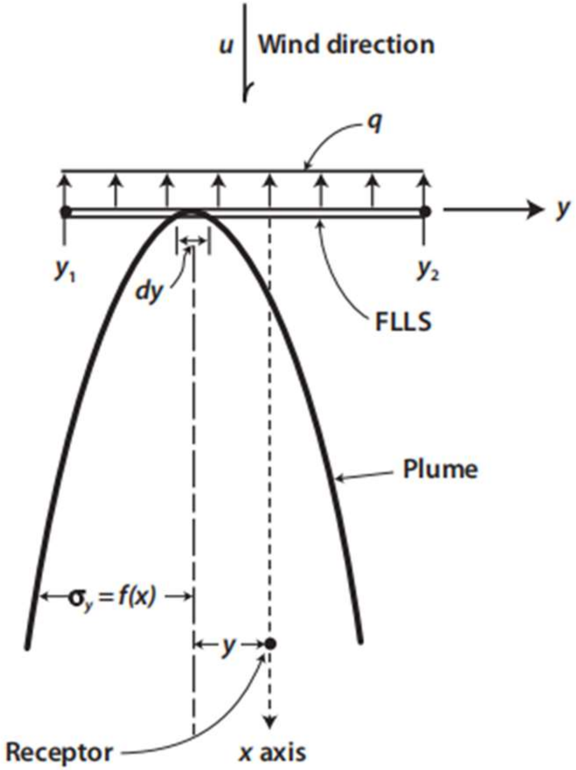

Figure 20.16
The finite length line source (FLLS) model.

$$dC = \frac{q\,dy}{2\pi u \sigma_y \sigma_z} \exp\left(-\frac{y^2}{2\sigma_y^2}\right)\left\{\exp\left[-\frac{(z-H)^2}{2\sigma_z^2}\right] + \exp\left[\frac{-(z+H)^2}{2\sigma_z^2}\right]\right\} \quad (20.25)$$

$$C = \frac{K}{2\pi\sigma_y}\int_{y_1}^{y_2} \exp\left(\frac{-y^2}{2\sigma_y^2}\right) dy \quad (20.26)$$

where

$$K = \frac{q}{u\sigma_z}\left\{\exp\left[\frac{-(z-H)^2}{2\sigma_z^2}\right] + \exp\left[\frac{-(z+H)^2}{2\sigma_z^2}\right]\right\} \quad (20.27)$$