CE 435: Environmental Pollution Management

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Level-4, Term II

CN-5

Department of Civil Engineering

Bangladesh University of Engineering and Technology (BUET)

Air Quality Modeling

Air Quality Modeling

Air quality models use mathematical and numerical techniques to simulate the physical and chemical processes that affect air pollution as they disperse and react in the atmosphere

Types of Air Quality Models

(1) **Dispersion/Diffusion Models:** uses mathematical formulations to characterize atmospheric processes that disperse a pollutant emitted by a source.

(2) **Photo-chemical Models**: Long-range air quality models that simulate the changes of pollutant concentrations in the atmosphere due to the chemical and physical processes in the atmosphere.

(3) **Receptor Models:** Mathematical and statistical procedures for identifying and quantifying the source of pollutants at a receptor location.

Point Source Gaussian Plume Model: A Diffusion Model

Goal: **To be able to describe mathematically the spatial and temporal distribution of contaminants released into the atmosphere from a point source.**

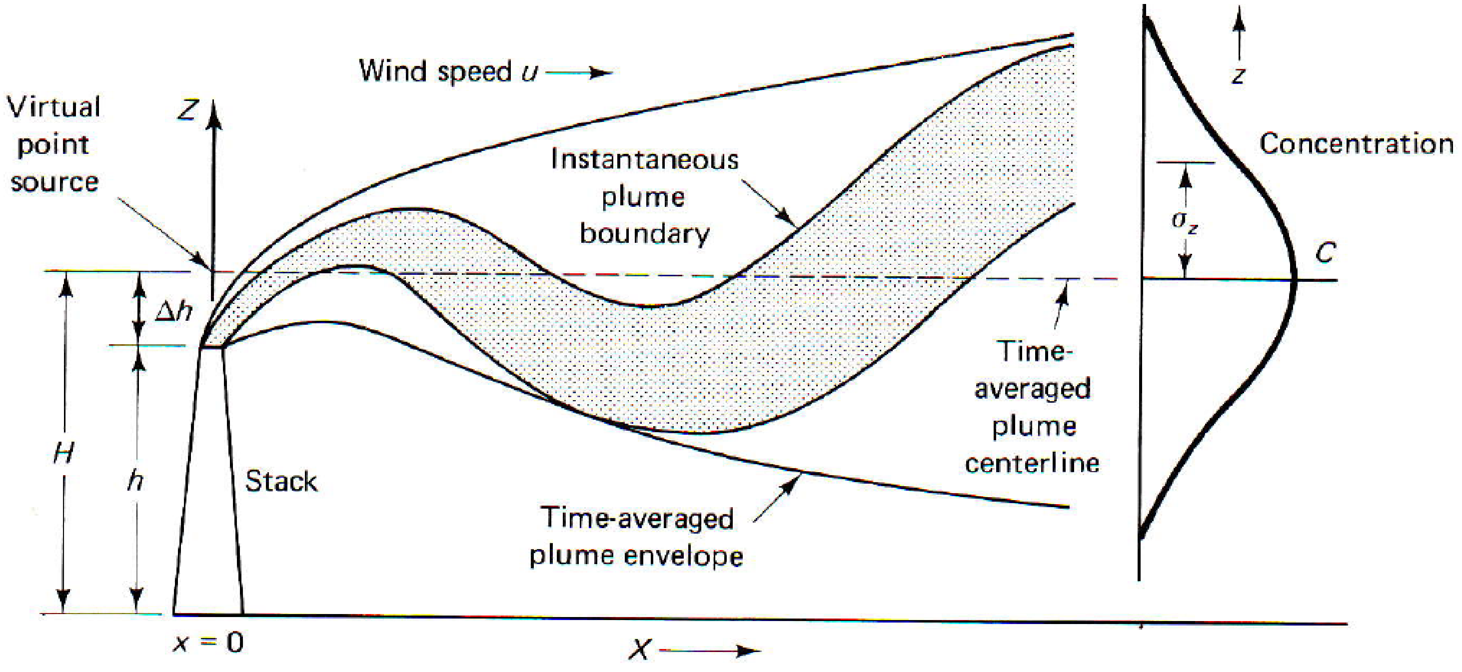


Figure 7.26 The instantaneous plume boundary and a time-averaged plume envelope.

Assumptions of Point Source Gaussian Plume Model

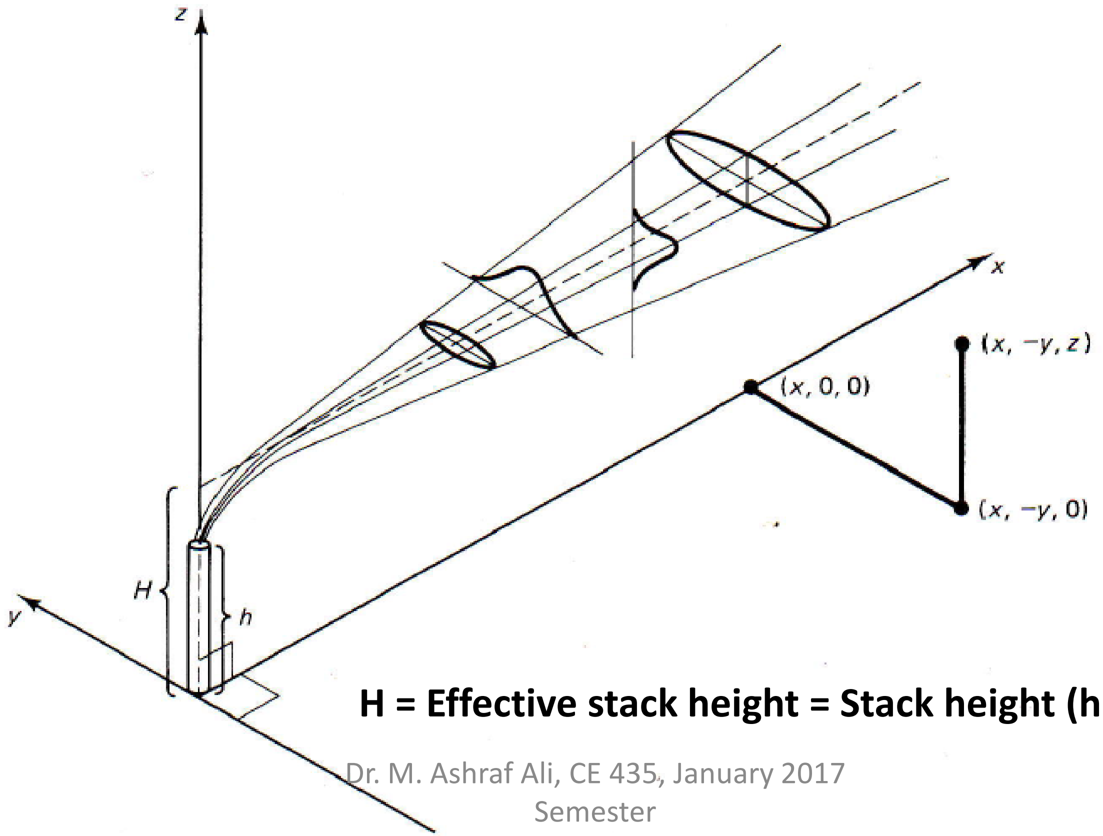
1) **Pollutant materials takes on Gaussian distribution in both Y and Z directions.**
2) **Steady state condition.**
3) **Ideal gas.**
4) **Uniform continuous emission rate.**
5) **No diffusion in X direction.**
6) **Homogenous horizontal wind field; wind speed constant.**
7) **Flat terrain.**

The basic Gaussian plume model applies to a single "point source" (e.g. smokestack), but it can be modified to account for "line source" (e.g. emissions from vehicles in a highway) or "area source".

Gaussian Plume Model Equations: Point Source

(A) No ground reflection (e.g. particles, nitric acid vapor):

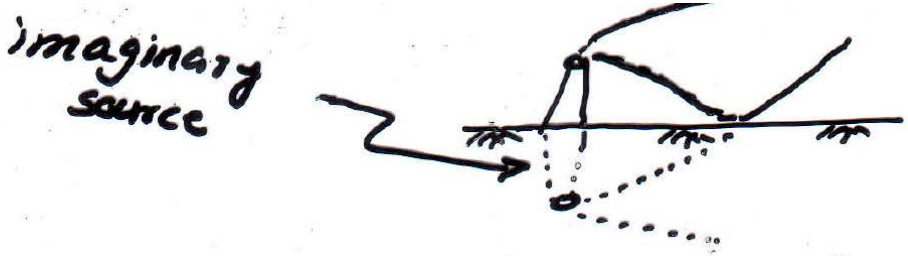
$$C(x,y,z) = \frac{Q}{2\pi \sigma_y \sigma_z u} \exp\left[-\frac{y^2}{2\sigma_y^2}\right] \exp\left[\frac{-(z-H)^2}{2\sigma_z^2}\right]$$



H = Effective stack height = Stack height (h) + Plume rise (Δh)

Gaussian Plume Model Equations: Point Source

(B) With ground reflection (e.g. CO, NO_2, SO_2):

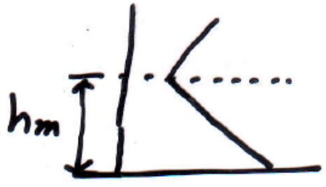


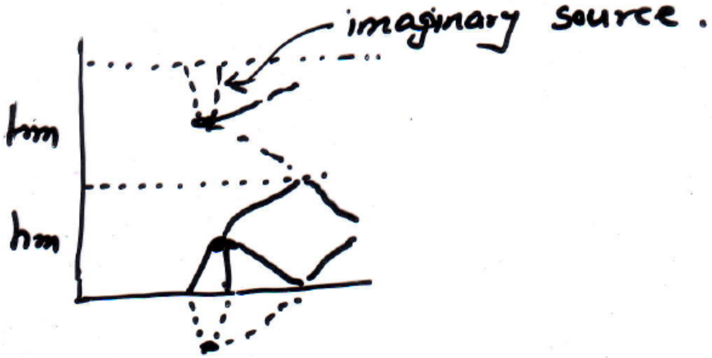
$$c\,(x,y,z) = \frac{Q}{2\pi\sigma_y\sigma_z\bar{u}}\exp\left[-\frac{y^2}{2\sigma_y^2}\right]\left\{\exp\left[-\frac{(z-H)^2}{2\sigma_z^2}\right] + \exp\left[-\frac{(z+H)^2}{2\sigma_z^2}\right]\right\}$$

where, c = pollutant concentration (mg/m^3, $\mu g/m^3$)
Q = uniform continuous emission rate (g/s, µg/s)
$\bar{u}$ = mean wind speed at plume height (m/s)
σ_y = cross-wind (y-direction) dispersion parameter (m)
σ_z = vertical (z-direction) dispersion parameter (m)
x, y, z = location of receptor
H = Effective stack height (= stack height, h + plume rise, Δh)

Gaussian Plume Model Equations: Point Source

(C) With ground reflection and temperature inversion:





$$C(x,y,z) = \frac{Q}{2\pi\sigma_y\sigma_z\bar{u}}\exp\left[-\frac{y^2}{2\sigma_y^2}\right]\left\{\exp\left[-\frac{(z-H)^2}{2\sigma_z^2}\right]\right.$$

$$+\exp\left[-\frac{(z+H)^2}{2\sigma_z^2}\right]+\exp\left[-\frac{(z-H-2h_m)^2}{2\sigma_z^2}\right]$$

$$+\exp\left[-\frac{(z-H+2h_m)^2}{2\sigma_z^2}\right]+\exp\left[-\frac{(z+H-2h_m)^2}{2\sigma_z^2}\right]$$

$$\left.+\exp\left[-\frac{(z+H+2h_m)^2}{2\sigma_z^2}\right]\right\}$$

Simplification of Gaussian Plume Equations under various conditions

(a) Concentration at ground level (z = 0), with no inversion layer ($h_m = 0$) (with ground reflection)

$$c(x,y,0) = \frac{Q}{\pi \bar{u} \sigma_y \sigma_z} \exp\left(-\frac{y^2}{2\sigma_y^2}\right) \exp\left(-\frac{H^2}{2\sigma_z^2}\right)$$

(b) Concentration at ground level (z = 0), along center-line (y = 0), with no inversion layer ($h_m = 0$) (with ground reflection)

$$c(x,0,0) = \frac{Q}{\pi \bar{u} \sigma_y \sigma_z} \exp\left(-\frac{H^2}{2\sigma_z^2}\right)$$

(c) Concentration at ground level (z = 0), along center-line (y = 0), with no inversion layer ($h_m = 0$), for emission at ground level (H = 0) (with ground reflection)

$$c(x,0,0) = \frac{Q}{\pi \bar{u} \sigma_y \sigma_z}$$

Determination/ Estimation of Parameters of Gaussian Plume Equation

(1) Q = Emission rate; usually expressed in g/s

Estimated based on available information on emission (see examples)

Estimation of Emission Rate (Q)

Ex. 1: **A power plant consumes 200 tons of coal (containing 1.5% Sulfur by weight) each day. Assuming 9% of this Sulfur (S) is emitted as SO_2, estimate the emission rate of SO_2 (in g/s) from the power plant.**

Estimation of Emission Rate (Q)

Ex. 2: The following information is available on emission of NO_x for the under-construction 335 MW combined cycle (CC) power plant (gas-based) at Siddhirganj Power Generation Complex.

Flow rate of exhaust gas = 589.4 kg/s
Maximum NO_x in exhaust gas = 25 ppmv

Estimate NO_x emission rate from the power plant in "g NO_x/s"

[Given: MW of exhaust gas = 28.01 g/mol; assume all NO_x emitted as NO_2)

Determination/ Estimation of Parameters of Gaussian Plume Equation

(2) H = Effective Stack Height

= Stack height (h) + Plume rise (Δh)

- The extent of “plume rise” depends primarily on the “buoyancy” and “momentum” of exhaust gas and “stability” of the atmosphere.
- “Buoyancy” results when exhaust gases are hotter than the ambient air and/or when the molecular weight of the exhaust gas is lower than that of air.
- “Momentum” is caused by the mass and velocity of the gases as they leave the stack.

Estimation of Plume Rise (Δh)

Different techniques are used for estimation of "plume rise". The USEPA recommends the following model:

The buoyancy flux parameter is given by:

$$F = g\, r^2 v_s (1 - T_a/T_s)$$

where, F = buoyancy flux parameter (m^4/s^3)
g = gravitational acceleration ($=9.8\ m/s^2$)
r = inside radius of stack (m)
v_s = stack gas exit velocity (m/s)
T_s = stack gas temperature (K)
T_a = ambient air temperature (K)

For "neutral" or "unstable" atmosphere (Stability Class A-D), "plume rise" is given by: $\Delta h = (1.6\, F^{1/3}\, x_f^{2/3})/u$

where, u = wind speed at stack height (m/s)
x_f = distance downwind to point of final plume rise

The following is often used to estimate x_f:

$x_f = 120\ F^{0.4}$; if $F \geq 55\ m^4/s^3$
$x_f = 50\ F^{5/8}$; if $F < 55\ m^4/s^3$

Estimation of Plume Rise (Δh) (contd.)

For “stable” conditions (Stability Class E and F), plume rise is given by:

$$\Delta h = 2.6 \left(\frac{F}{uS} \right)^{1/3}$$

The quantity “S” is a stability parameter, with unit of s^{-2}, and is given by,

$$S = \frac{g}{T_a}\left(\frac{\Delta T_a}{\Delta z} + \Gamma \right) = \frac{g}{T_a}\left(\frac{\Delta T_a}{\Delta z} + 0.01\ {}^{\circ}\mathrm{C/m} \right)$$

“$\Delta T_a / \Delta z$” represents the actual rate of change of ambient temperature with altitude; a positive value means temperature is increasing with altitude.

Estimation of Effective Stack Height (H)

Ex. 3: A power plant has a 100 m stack with an inside radius of 1m. The exhaust gases leave the stack with an exit velocity of 10 m/s at a temperature of 120 °C. Ambient temperature is 6 °C. Wind speed at the stack height is estimated to be 5 m/s; surface wind speed is 3 m/s, and it is a cloudy summer day. Estimate the effective stack height.

Soln.
$r = 1$ m
$v_s = 10$ m/s
$T_s = 120 + 273 = 393$ K
$T_a = 6 + 273 = 279$ K
$u = 5$ m/s

Surface wind speed = 3 m/s
"Cloudy summer day"
$\therefore$ From Table 7.8,
Stability Class = C
(Slightly unstable)

Now, $F = g\, r^2 v_s (1 – T_a/T_s) = 9.8 \times (1)^2 \times 10 (1 – 279/393) = 28.4\ m^4/s^3$
$\therefore x_f = 50\, F^{5/8} = 50\, (28.4)^{5/8} = 404.8$ m
$\therefore \Delta h = (1.6\, F^{1/3}\, x_f^{2/3})/u = [1.6\, (28.4)^{1/3} \times (404.8)^{2/3}]/5 = 53.4$ m

Effective Stack Height = $h + \Delta h = 100 + 53.4 = 153.4$ m

If the atmosphere is "stable" (stability class F), and $\Delta T_a/\Delta z = 0$ (i.e. isothermal), estimate Δh and H

$S = (g/T_a)\, (\Delta T_a/\Delta z + \Gamma) = (9.8/279)\, (0 + 0.01) = 3.5 \times 10^{-4}\ s^{-2}$

$\therefore\ \Delta h = 2.6\, (F/uS)^{1/3} = 2.6\, [28.4/(5 \times 3.5 \times 10^{-4})]^{1/3} = 65.8$ m

Effective Stack Height = $h + \Delta h = 100 + 65.8 = 165.8$ m

Determination/ Estimation of Parameters of Gaussian Plume Equation

(3) $\bar{u}$ = mean wind speed at plume height

$\bar{u}(z) = \bar{u}_o\,(z/z_o)^p$; usually valid for up to few hundred meter above ground level

where,

$\bar{u}(z)$ = wind speed at plume height z

$\bar{u}_o$ = wind speed at instrument height

z = plume height

z_o = instrument height (usually 10 m)

p = a factor which depends on stability condition of atmosphere, and can be taken from Table 7.7

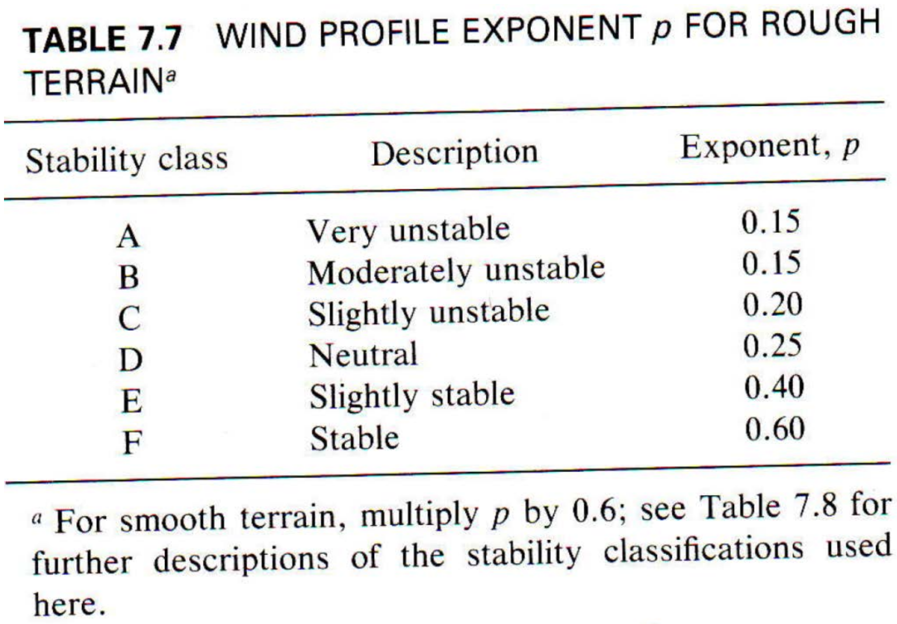


TABLE 7.7 WIND PROFILE EXPONENT *p* FOR ROUGH TERRAIN[a]

Stability class	Description	Exponent, *p*
A	Very unstable	0.15
B	Moderately unstable	0.15
C	Slightly unstable	0.20
D	Neutral	0.25
E	Slightly stable	0.40
F	Stable	0.60

[a] For smooth terrain, multiply *p* by 0.6; see Table 7.8 for further descriptions of the stability classifications used here.

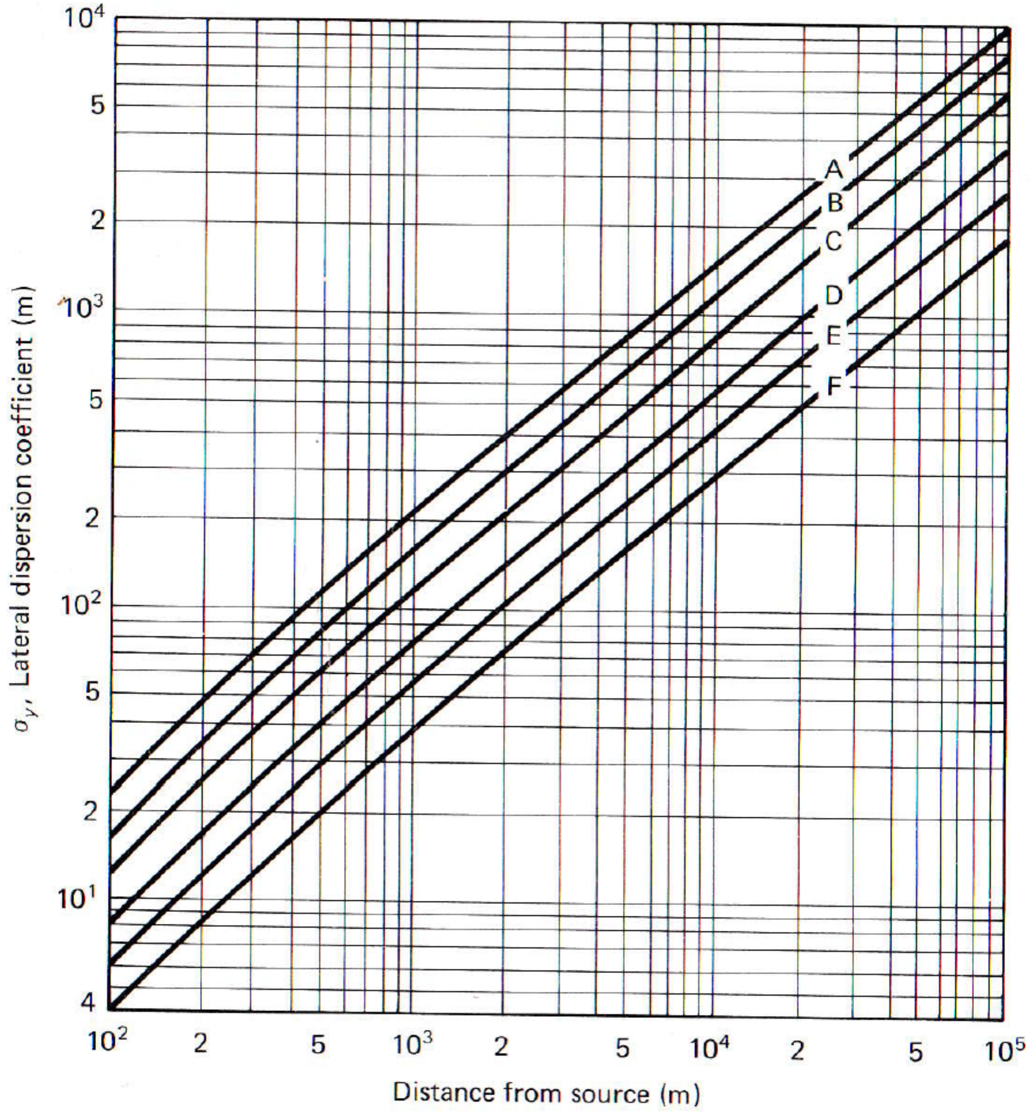
Determination/ Estimation of Parameters of Gaussian Plume Equation

(4) σ_y, σ_z = dispersion parameter
σ_y, σ_z = f (distance, "stability" condition)

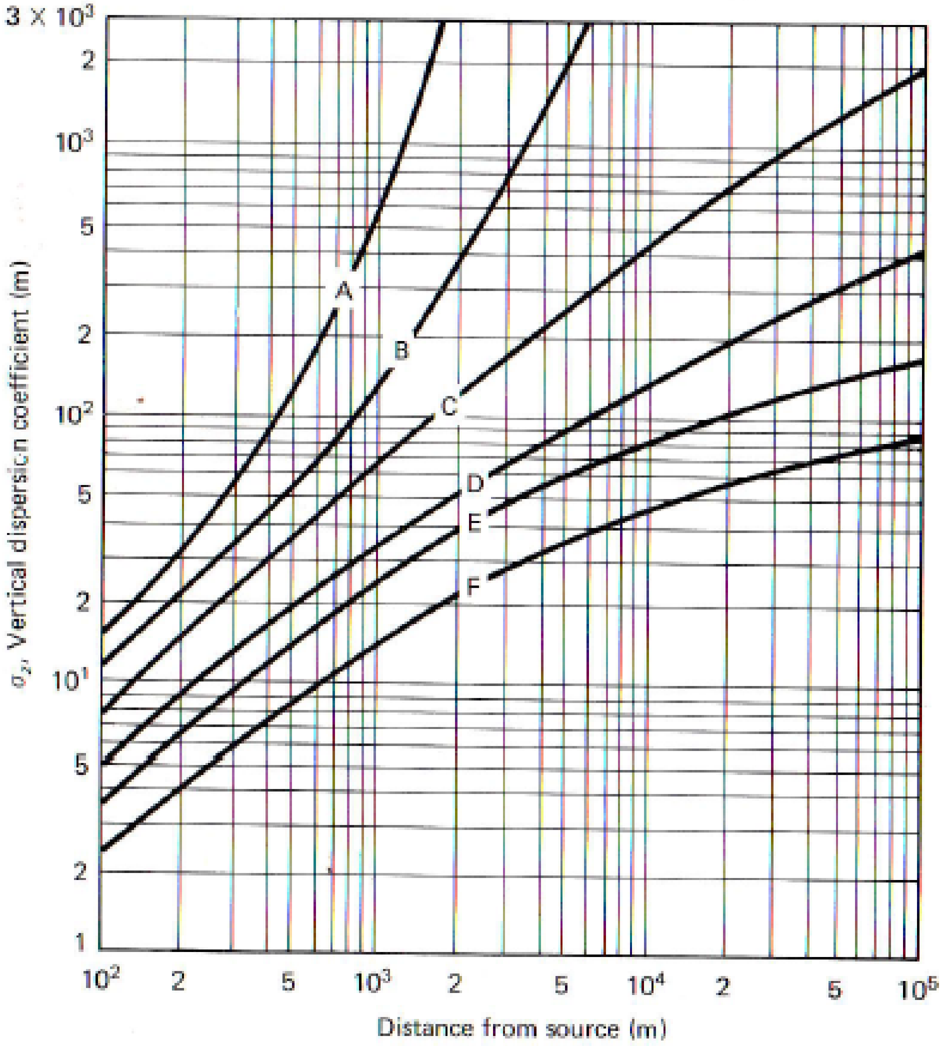
These are standard deviations, and can be obtained from plots of σ_y and σ_z versus distance downwind for different stability conditions (see plots). In general,

- As distance downstream (x) increases, σ_y and σ_z increase
- For a given distance x, σ_y and σ_z increase as we move to more unstable condition
- There are different approaches for estimating σ_y and σ_z

Estimation of σ_y



Estimation of σ_z



Estimation of σ_y and σ_z (Martin, 1976)

$\sigma_y = a.x^{0.894}$

$\sigma_z = c.x^d + f$

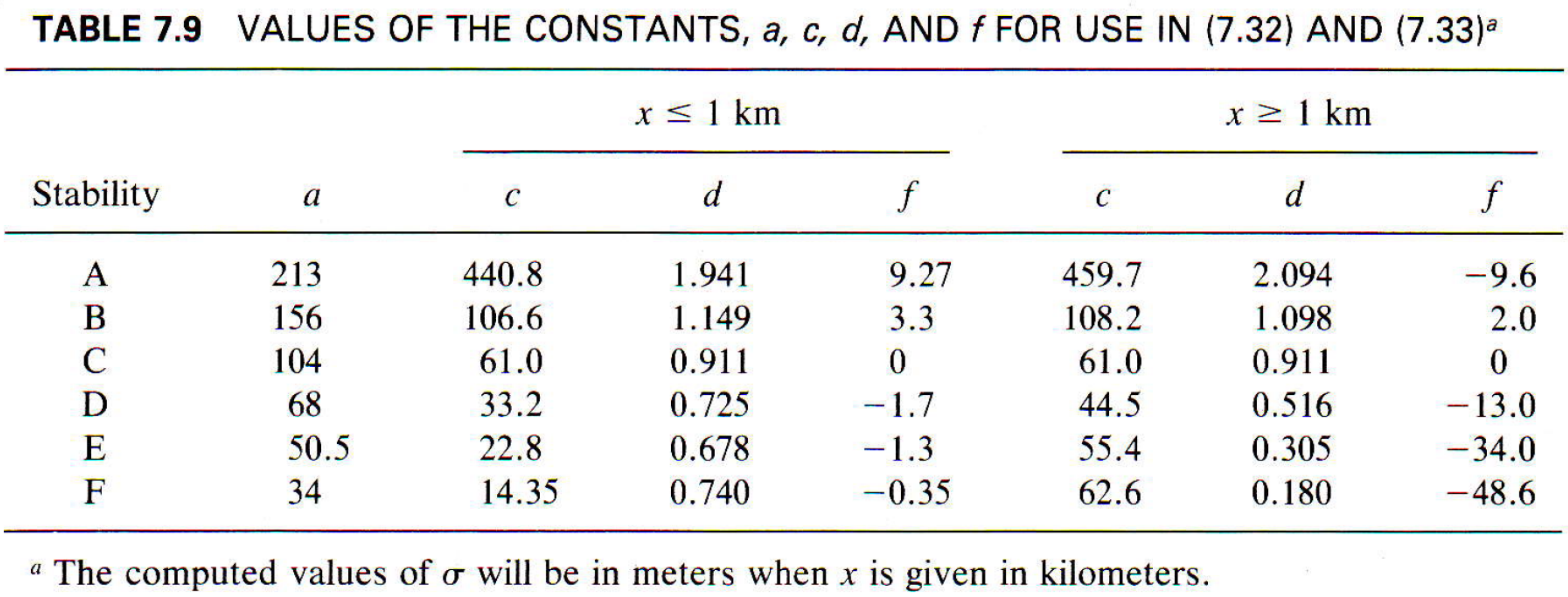


TABLE 7.9 VALUES OF THE CONSTANTS, *a, c, d,* AND *f* FOR USE IN (7.32) AND (7.33)[a]

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

[a] The computed values of σ will be in meters when x is given in kilometers.

Example Problems

Ex. 4: A stack emitting 80 g/s of NO has an effective height of 100 m. The wind speed is 4 m/s at 10 m height, and it is a clear summer day with the sun nearly overhead. Estimate the ground level NO concentration:

(a) directly downwind at a distance of 2 km;
(b) at a point 2 km downwind and 0.1 km off the downwind axis; and
(c) at a point downwind where NO is maximum

Example Problems

Soln.(c): "Peak down-wind concentration" can be estimated using the following Chart.

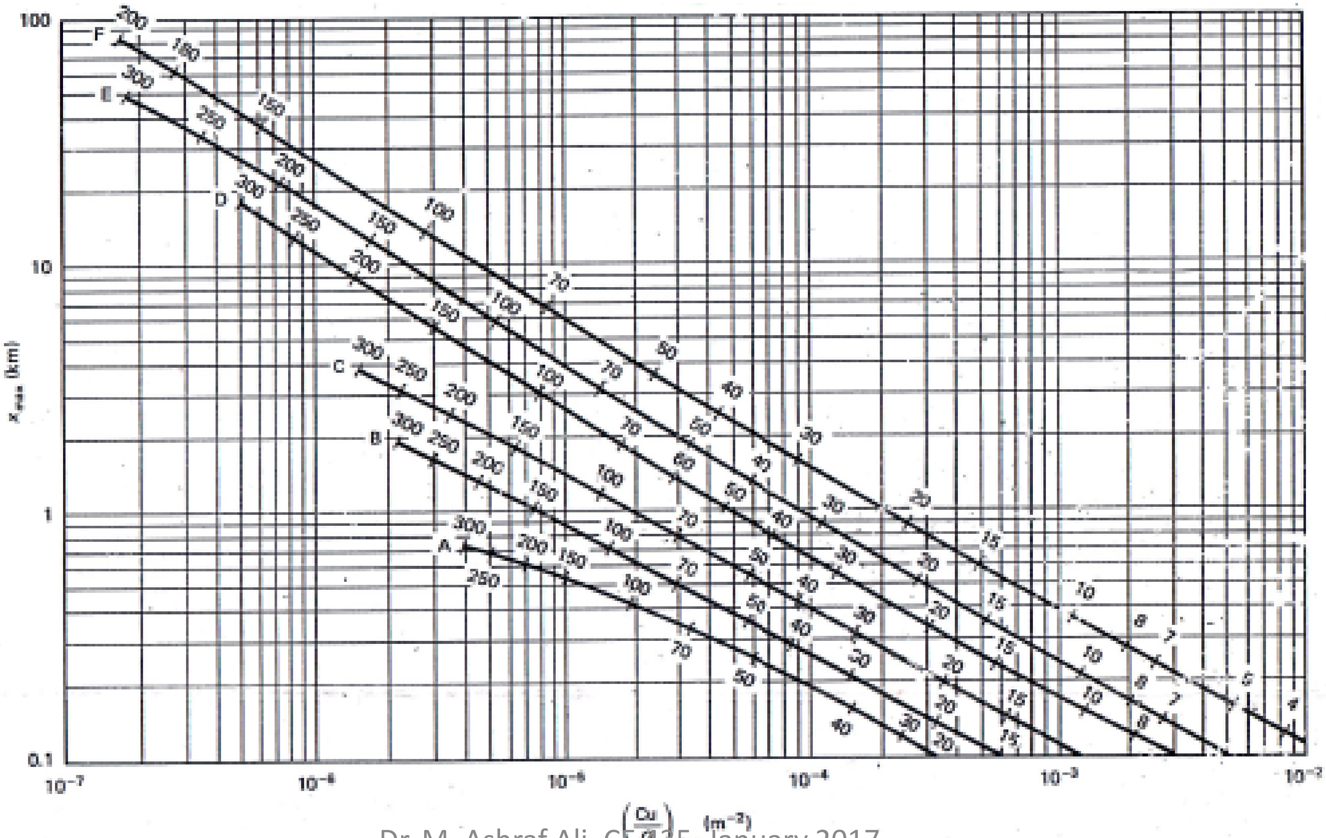
$C_{max} = (Q/\bar{u}).(C.\ \bar{u}/Q)_{max}$

If "stability class" and "H" are known, then we can estimate:

(a) distance to peak, and

(b) $(C.\ \bar{u}/Q)_{max}$, from the Chart

Then, the above equation can be used to estimate C_{max}



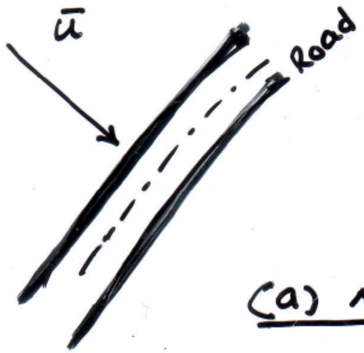
Gaussian Plume Model Equations: Line Source

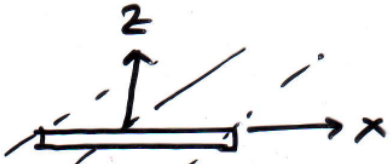
Examples of "line source":

- **Motor vehicles traveling along a straight section of a highway;**
- **Agricultural burning along the edge of a field;**
- **A line of industrial sources on the bank of a river.**

Assumptions:

- **Infinite-length source at ground level; and**
- **Wind blowing perpendicular to the line**





$H \simeq 0$ for Road.

(a) No ground reflection:

$$C(x,z) = \frac{Q_L}{\sqrt{2\pi}\,\sigma_z \cdot \bar{u}} \exp\left[-\frac{(z-H)^2}{2\sigma_z^2}\right]$$

(b) With ground reflection:

$$C(x,z) = \frac{Q_L}{\sqrt{2\pi}\,\sigma_z\,\bar{u}} \left\{\exp\left[-\frac{(z-H)^2}{2\sigma_z^2}\right] + \exp\left[-\frac{(z+H)^2}{2\sigma_z^2}\right]\right\}$$

Example Problems

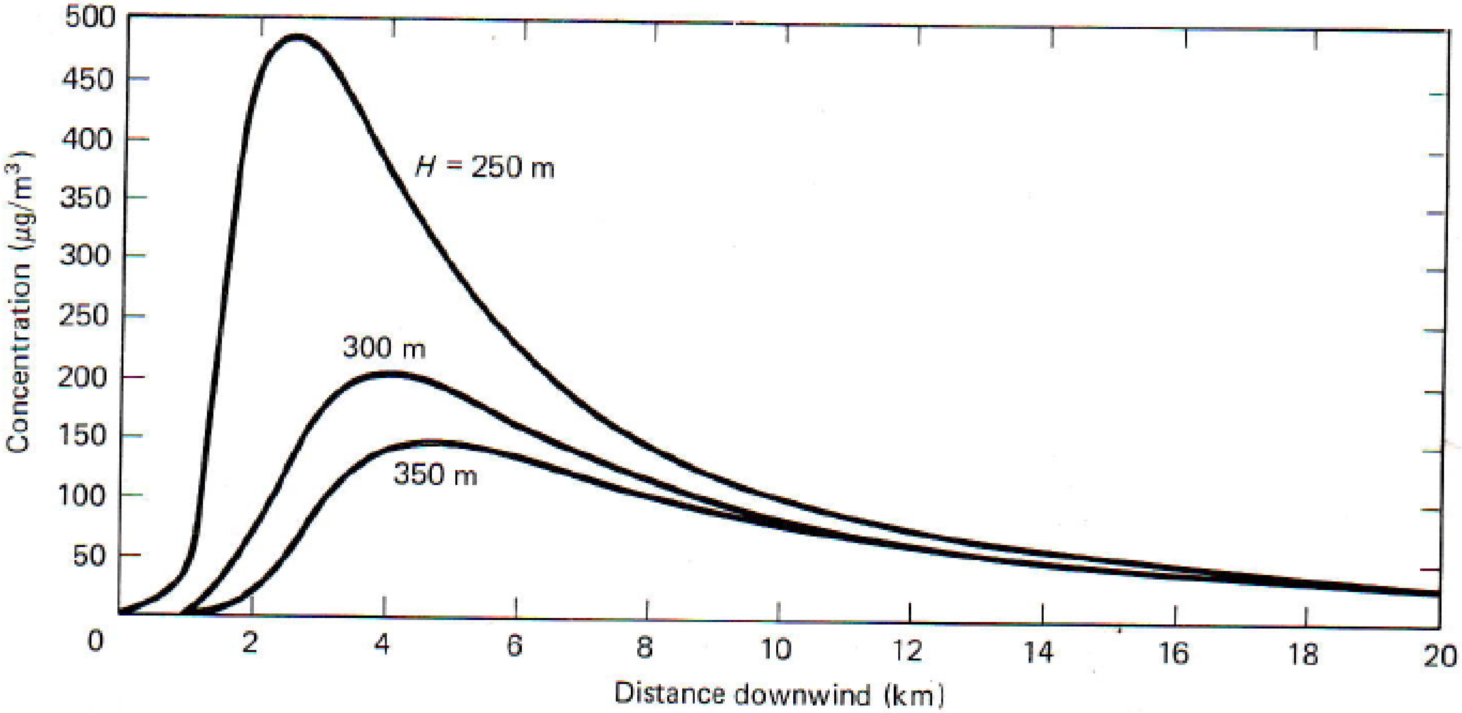
Ex. 5: Suppose a highway has 10 vehicles per second passing a given spot, each emitting 2.3 km of CO. The wind is perpendicular to the highway and blowing a 2.2 m/s. Estimate the ground level CO concentration 200 m from the highway, assuming atmosphere to be "adiabatic".

Effect of Stack Height (H) on Down-wind Concentration

Assumed conditions:

$Q = 647$ g SO_2/s
$\bar{u} = 4.9$ m/s
Stability Class = C
H = 250 m; 300 m; 350 m

Ground level concentration at any point (see Fig.) decreases as "H" increases.



Effect of Stability Class on Down-wind Concentration

Assumed conditions:

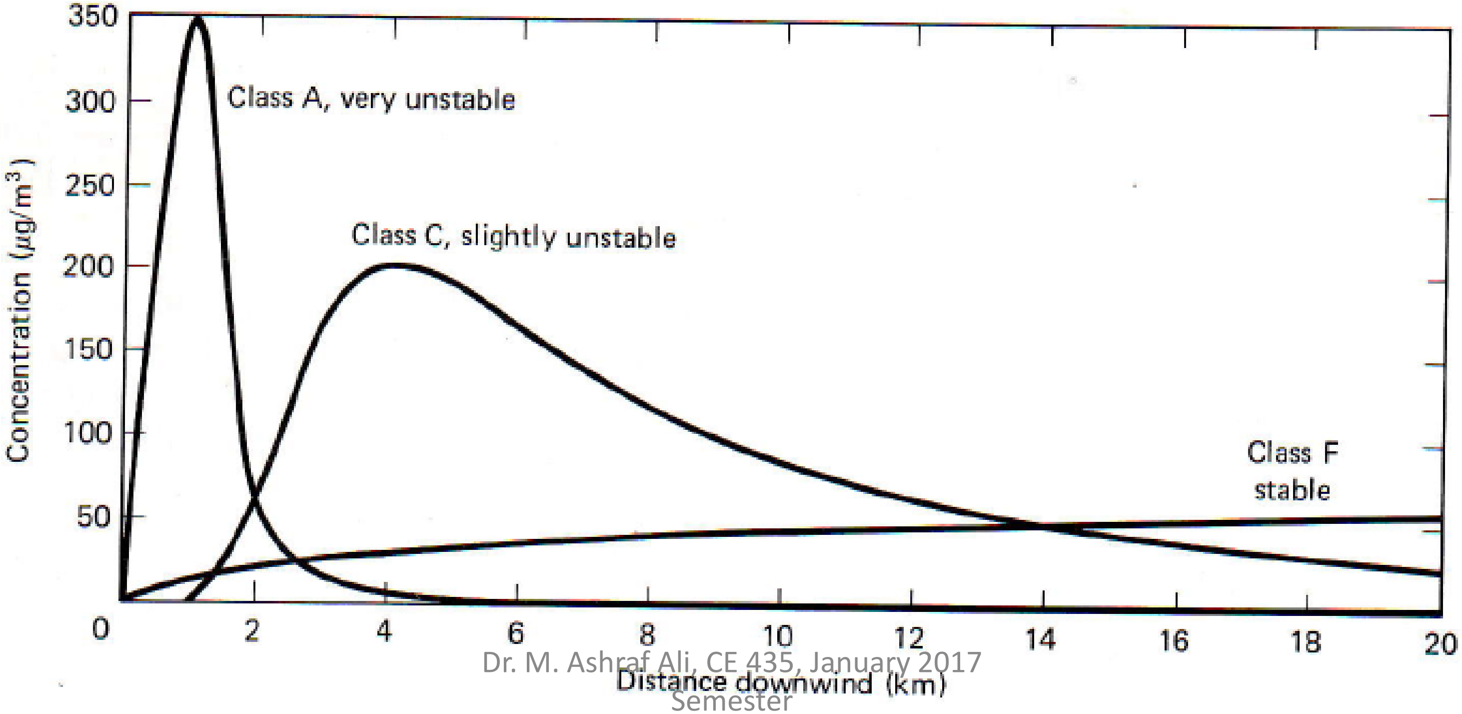
$Q = 647$ g SO2/s

$\bar{u} = 4.9$ m/s

$H = 300$ m

Stability Class = A; C; F

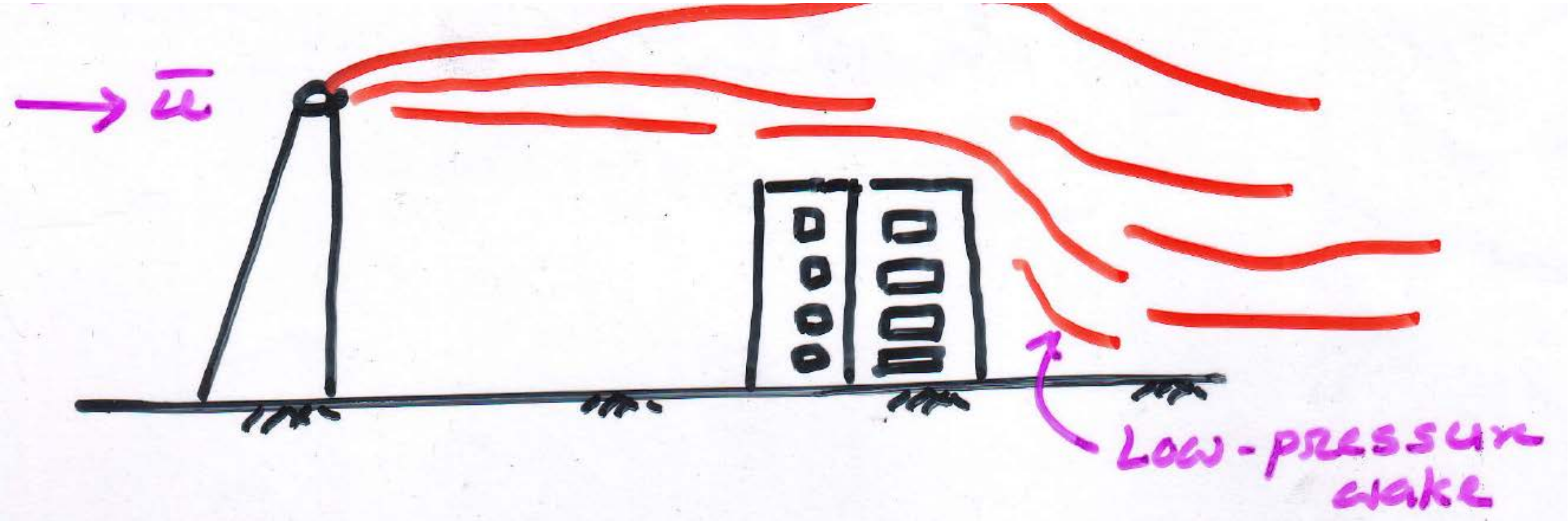
Effect of "stability class" depends on distance down-wind



Special Considerations

Building Wakes:

- **A plume may get sucked into the low-pressure wake behind a building, leading to a high level contamination.**
- **The simple rule of thumb for avoiding this problem is to make the stack height at least 2.5 times the height of the tallest nearby building.**



Special Considerations

Aerodynamic Downwash:

- **Aerodynamic downwash may significantly increase ground level concentration. It is a major problem for any facility located near a mountain.**