EVE 402/502
Air Pollution Generation and Control

Chapter #4
Dispersion of Pollutants
In the Atmosphere

"Transport and dilution of pollutants by air motions goes on constantly; and all of humanity, particularly that large segment inhabiting cities and industrial areas, depends strongly on this capability of the air to carry away and dilute the pollutants it receives. What we call "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. Thus we must…understand the atmospheric mechanisms that result in transport and dilution…"

F. A. Gifford, 1975

Introduction

- Atmospheric dispersion depends on
  - Physical/chemical nature of emissions
  - Meteorological characteristics
  - Stack location
  - Terrain downwind from stack
- No analytical method for estimating dispersion accounts for all of the above

Classifications of AQ Models

- Developed for a number of pollutant types and time periods
  - **Short-term** models – for a few hours to a few days; worst case episode conditions
  - **Long-term** models – to predict seasonal or annual average concentrations; health effects due to chronic exposures
- Classified as
  - **Non-reactive** models – pollutants such as CH_4 and CO
  - **Reactive** models – pollutants such as O_3, NO_2, etc.

Regulatory Application of Models

- **PSD**: Prevention of Significant Deterioration of Air Quality in relatively clean areas (e.g. National Parks)
- **SIP**: State Implementation Plan revisions for *existing sources* and to *New Source Reviews* (NSR)

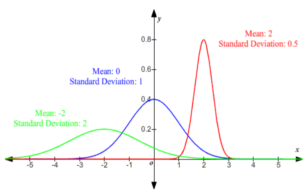

Characteristics of Dispersion Models

- The accuracy of dispersion models varies according to the complexity of the terrain and the sufficiency of historic meteorological data
- The acceptability of the results of dispersion models varies with the experience and viewpoint of the modeler, the regulator and the intervener

The Gaussian (Normal) Distribution

- A variable x is said to be normally distributed if:

$$y = f(x) = \frac{1}{\sigma(2\pi)^{1/2}} exp\left[\frac{-(x-\mu)^2}{2\sigma^2}\right]$$



y is the height of the curve for a given value of x

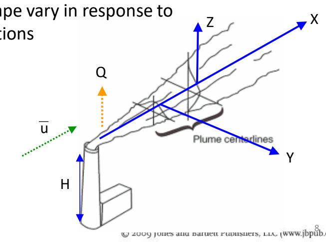
μ is the mean value of the distribution

σ is the standard deviation

What's the area under each curve?

Gaussian Dispersion Models

- Most widely used
- Based on the assumptions that
  - plume spread results primarily by **molecular diffusion**
  - horizontal and vertical pollutant concentrations in the plume are normally distributed (double Gaussian distribution)
- Plume spread and shape vary in response to meteorological conditions



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Characteristics of Pollutant Plume

- Horizontal (y) and vertical (z) dispersion is caused by eddies and random shifts of wind direction
- Key parameters are:
  - Physical stack height (h)
  - Plume rise (Δh)
  - Effective stack height (H)
  - Wind speed (u_x)

Other Gaussian Model Assumptions

- Steady-state conditions (constant source emission strength)
- Wind speed, direction and diffusion characteristics of the plume are constant
- Mass transfer due to bulk motion in the x-direction far exceeds the contribution due to mass diffusion
- Conservation of mass, i.e. no chemical transformations take place
- Wind speeds are $\geq$1 m/sec
- Limited to predicting concentrations > 50 m downwind

Gaussian Dispersion Equation – elevated source

$$C(x,y,z)=\frac{Q}{2\pi\sigma_y\sigma_z\bar{u}}\exp\left[-\frac{1}{2}\left(\frac{y^2}{\sigma_y^2}+\frac{(z-H)^2}{\sigma_z^2}\right)\right]$$

Why isn't x in the equation?

σ_y and σ_z depend on the atmospheric conditions

Atmospheric stability classifications are defined in terms of surface wind speed, incoming solar radiation and cloud cover

In this equation, the earth's surface is a ***sink*** for the pollutant (we'll come back to this…)

Reminder: Stability Categories

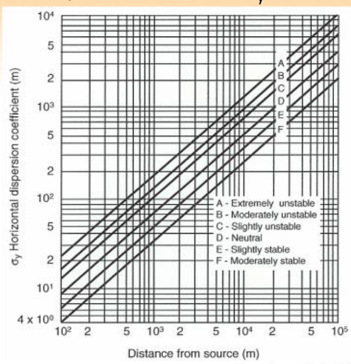
Figure 3-1

Surface Wind Speed[a] m/s	Day Incoming Solar Radiation			Night Cloudiness[e]	
	Strong[b]	Moderate[c]	Slight[d]	Cloudy (≥4/8)	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.

Pasquill-Gifford Curve (σ_y) - Rural



See Fig. 4-6 in text for urban overlay

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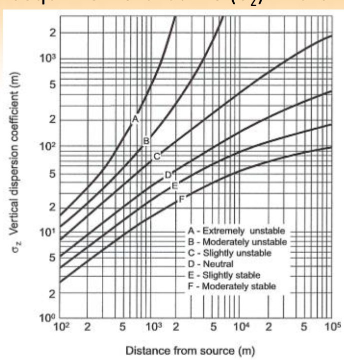
Pasquill-Gifford Curve (σ_z) - Rural



See Fig 4-7 in text for urban overlay

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To determine σ_y and σ_z

- Pasquill-Gifford Curves
  - Figure 4-6 (σ_y, urban and rural)
  - Figure 4-7 (σ_z, urban and rural)
- The curves aren't necessarily easy to read, though
  - Equations 4-12 through 4-14
  - Table 4-1 and 4-2
- McElroy-Pooler (Urban)
  - Table 4-3 and Table 4-4

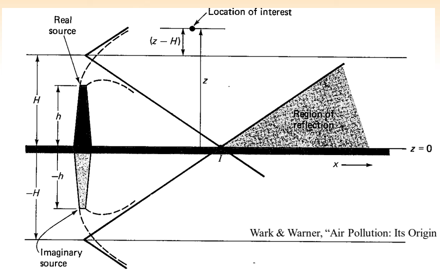
Note: The figures and correlations for estimating the dispersion coefficients correspond to sampling times of approximately **10 min**. Regulatory models assume **1 or 8 hour averages**

- Variation of concentration with averaging time:

  $C_t = C_{10}(10/t)^q$, where q = 0.17 - 0.20

  So, determine downwind concentration using model (C_{10}), then use equation above to determine concentration (C_t) for appropriate averaging time (t) in minutes

What if the surface of the earth is not a sink for the pollutant?



Wark & Warner, "Air Pollution: Its Origin & Control"

Figure 4-3 Use of an imaginary source to describe mathematically gaseous reflection at surface of the earth.

Concentration profile with surface reflection:

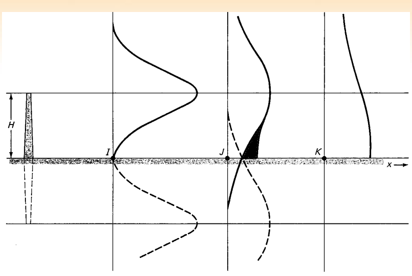


Figure 4-4 Effect of ground reflection on pollutant concentration downwind.

Elevated source with reflection (Eqn 4-8)

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

where C(x,y,z) = time averaged contaminant concentration,
Q = source emissions strength, g/s
u = mean wind speed at the effective stack height, m/s
σ_y = dispersion coefficient in the crosswind direction, m
σ_z = dispersion coefficient in the vertical direction, m
y = horizontal distance from centerline, m
z = vertical distance from centerline, m
H = effective stack height = h + Δh
h = stack height, m
Δh = plume rise, m

The model assumes that there is a continuous point source emission, crosswind and vertical dispersion are Gaussian in nature, plume moves downwind at a rate equal to u, no particles settle out, downwind dispersion is negligible compared to the bulk wind motion, and that the pollutants are inert.

Delete

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

The **maximum downwind concentration** will occur on the plume centerline where y = 0. Assuming an elevated source, Equation 4-8 simplifies to:

$$C(x,0,z)=\frac{Q}{2\pi u\sigma_y\sigma_z}\left\{\exp\left[\frac{-(z-H)^2}{2\sigma_z^2}\right]+\exp\left[\frac{-(z+H)^2}{2\sigma_z^2}\right]\right\}$$

Many receptors of concern will be located at ground level such that z = 0. With an elevated source, the downwind, ground level concentration can be estimated as follows:

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

The ground level concentration, occurring on the center line is easily determined by substituting y = 0 the above equation

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

Finally, if a ground level source such as a landfill is assumed, the effective stack height can be modeled as H = 0. If the center line, ground level concentration is desired, the previous equation is simplified as follows:

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

Maximum Ground Level Concentration

Under moderately unstable to near neutral conditions,

$\sigma_y = k_1 \sigma_z$

The ground level concentration at the center line is

$$C(x,0,0) = \frac{Q}{\pi k_1 \sigma_z^2 u} \exp\left[-\frac{H^2}{2\sigma_z^2} \right]$$

The maximum occurs at

$$dC/d\sigma_z = 0 \quad \Rightarrow \sigma_z = \frac{H}{\sqrt{2}}$$

Once σ_z is determined, x can be known and subsequently C.

$$C(x,0,0) = \frac{Q}{\pi \sigma_y \sigma_z u} \exp[-1] = 0.1171 \frac{Q}{\sigma_y \sigma_z u}$$

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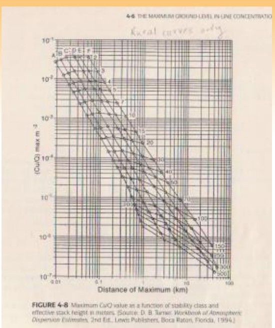
Alternate Method to Find Max GL Conc Figure 4-8 (Rural only)



A general equation was fit to the data so the solution can be found algebraically.

Equation 4-15

Table 4-5 (for a, b, c, d)

$$\left(\frac{Cu}{Q}\right)_{\max} = \exp\left[a + b(\ln H) + c(\ln H)^2 + d(\ln H)^3 \right]$$

Plume Rise (Δh) equations are usually expressed as a function of:

- Momentum term – accounts for vertical momentum of stack gas due to its own velocity
- Buoyancy term – accounts for the difference in stack gas and environmental temperatures

Commonly used empirical equations for plum rise include:

- Carson and Moses (Eqn 4-18)
- Holland Equation (4-19) – good for tall stacks
- Thomas Equation (4-21)

Correct Units are Important!!

Briggs Equations (4-22 through 4-35) are most commonly used

Table 4-6 provides a flow diagram

Example

For an overcast winter night, (a) estimate the maximum ground-level SO_2 concentration 10km downwind from a copper smelter if the wind speed is 3 m/s at 10 m. Assume h = 100m, Δh = 150 m, and an urban environment. (b) Estimate the maximum ground-level concentration along the center line. Assume a source strength of 5027 g/s of SO_2.

Example

- An industrial boiler in a rural area is burning at 12 tons (10.9 mton) of 2.5% sulfur coal/hr. The following conditions exist : H = 120 m, u = 2 m/s (measured at 10m), y = 0. It is one hour before sunrise, and the sky is clear. Determine downwind ground level concentration of SO_2 at 10 km.

Stability class =

σ_y =

σ_z =

C(10 km, 0, 0) =

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Exercise

- If emissions are from a ground level source with H = 0, u = 4 m/s, Q = 100 g/s, and the stability class = B, what is downwind concentration at 200 m?

At 200 m:

σ_y =

σ_z =

C(200 m, 0, 0) =

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Example

- Calculate H using plume rise equations for an 80 m high source (h) with a stack diameter = 4 m, stack velocity = 14 m/s, stack gas temperature = 90° C (363 K), ambient temperature = 25 °C (298 K), u at 10 m = 4m/s, and stability class = B. Then determine MGLC at its location.

F =

$\Delta h_{plume\ rise}$ =

H =

σ_z =

σ_y =

C_{max} =

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