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Principles of Air Pollution and Control

PDH: 5.0 Hours

Dr. M. A. Karim, P.E., F. ASCE

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Principles of Air Pollution and Control

1. Course Overview

This course introduces an overview of Physical and Chemical Fundamentals such as Ideal Gas Law, Dalton's Law and Partial Pressure; Adiabatic Expansion and Compression; Units of Measure; Air Pollution Perspective; Air Pollution Standards; Effects of Air Pollutants on Materials, Vegetation, and Health; Origin and Fate of Air Pollutants such as Carbon Monoxide, Hazardous Air Pollutants (HAPs), Lead, Nitrogen Dioxide, Photochemical Oxidants, Sulfur Oxides and Particulates; Micro and Macro Air Pollution; Contemporary Issues such as Acid Rain, Ozone Depletion, Greenhouse Effect; Impacts of Engineering Solutions in Global, Economic, Environmental and Societal Context; Air Pollution Meteorology such as the Atmospheric Engine, Turbulence, Stability, and Terrain Effects; Atmospheric Dispersion, Factors Affecting Dispersion of Air Pollutants, and Dispersion Modeling; Indoor Air Quality Model; Air Pollution Control of Stationary Sources such as Gaseous Pollutants, Flue Gas Desulfurization, Control Technologies for Nitrogen Oxides, and Particulate Pollutants. This course is suggested for civil engineers, environmental engineers, air permitting policy makers and consultants, and air pollution monitoring and control managers and equipment operators.

2. Learning Objectives

Upon successful completion of this course, the participants will be able to:

- identify/interpret the criteria air pollutants.
- describe the importance of air pollution standards and units of measurements.
- interpret the effects of air pollutants on vegetation, materials, and health.
- identify the origin and fate of air pollutants.
- explain the contemporary issues.
- discuss the air pollution meteorology.
- estimate air pollutant concentrations in the downstream using dispersion model.
- recognize the technologies and control devices used to control air pollutants.

3. Introduction

Air pollution is a gas, or a liquid or solid dispersed through ordinary air, released in a large enough quantity to affect the health of people and animals, damage crops or stop them growing properly, and make our world unpleasant and unattractive in a variety of other ways.

As with [water pollution](#) and [land contamination](#), it's the quantity (or **concentration**) of a chemical in the air that makes the difference between "harmless" and "pollution." Carbon dioxide (CO₂), for example, is present in the air around you at a typical concentration of less than 0.05 percent and breathing it in usually does no harm (you breathe it out all day long); but air with an extremely high concentration of carbon dioxide (say, 5–10 percent) is toxic and could kill you in a matter of minutes¹.



Figure 1: Natural air pollution

What are the causes of air pollution?

Anything people do that involves burning things (combustion), using household or industrial chemicals (substances that cause chemical reactions and may release toxic gases in the process), or producing large amounts of dust has the potential to cause air pollution. Step back a century or two and the cause of most air pollution was easy to identify: filthy factories and power plants, driving the Industrial Revolution. Today, better technology, tighter air pollution laws, greater environmental awareness, and determined campaigns mounted by local communities make it far harder—though by no means impossible—for factories to pollute in post-industrial nations such as the United States and Britain. But this type of "old-school" pollution remains a major problem in rapidly industrializing nations such as China and India.

Where, then, does modern air pollution come from? In developed countries such as the United States and the UK, by far the biggest culprit today is traffic, though power plants and factories continue to make an important contribution. Before we start laying the blame for air pollution, let's remember one very important thing: most of us drive (or travel in) cars, use [electricity](#), and buy goods made in factories.

¹ [NASA Earth Fact Sheet](#), 02 April 2020, gives the concentration of carbon dioxide as 410 parts per million or 0.04 percent. According to the [US CDC](#), "100,000 ppm is the atmospheric concentration immediately dangerous to life" (roughly 250 times greater).

3.1 Ideal Gas Law

Although polluted air may not be “ideal” from the biological point of view, we may treat its behavior with respect to temperature and pressure as if it is ideal.

Different kinds of gases have densities proportional to their molecular masses. This may be written as:

$$\rho = \frac{1 PM}{R T} \dots\dots\dots (1)$$

Where, ρ = density of gas, kg/m³

P = absolute pressure, kPa

M = molecular mass, grams/mole

T = absolute temperature, K

R = universal gas constant = 8.3143 J/K.mole

Since density is mass per unit volume, or the number of moles per unit volume, n/V , the expression may be rewritten in the general as:

$$PV = nRT \dots\dots\dots (2)$$

Where, V = volume occupied by n moles of gas

At 273.15K and 101.325 kPa, one mole of an ideal gas occupies 22.414 L.

3.2 Dalton’s Law and Partial Pressure

Stack and exhaust sampling measurements are made with instruments calibrated with air. Because combustion products have an entirely different composition than air, the reading must be adjusted to reflect this difference. Dalton’s law forms the basis for the calculation of the correction factor. Dalton found that the total pressure exerted by a mixture of gases is equal to the sum of the pressures that each type of gas would exert if it alone occupied the container. In mathematical terms,

$$P_t = P_1 + P_2 + P_3 + \dots\dots\dots (3)$$

where,

P_t = total pressure of mixture

P_1, P_2, P_3 = pressure of each gas if it were in container alone, that is partial pressure.

Dalton’s law also may be written in terms of ideal gas law:

$$P_t = n_1 \frac{RT}{V} + n_2 \frac{RT}{V} + n_3 \frac{RT}{V} + \dots\dots\dots = (n_1 + n_2 + n_3 + \dots) \frac{RT}{V} \dots\dots\dots (4)$$

3.3 Adiabatic Expansion and Compression

Air pollution meteorology is, in part, a consequence of the thermodynamic processes of the atmosphere. One such process is adiabatic expansion and contraction. An adiabatic process is one that takes place with **no addition or removal of heat and with sufficient slowness so that the gas can be considered to be in equilibrium at all times**. Since no heat enters or leaves the gas, the work will go into increasing the thermal energy of gas in accordance with the first law of thermodynamics, that is

$$(\text{Head added to gas}) = (\text{increase in thermal energy}) + (\text{external work done by or on the gas}) \dots\dots (5)$$

In adiabatic process, left side is zero, therefore, the increase in thermal energy is equal to the work done.

3.4 Units of Measure

Three basic units of measurement used in reporting air pollution data are:

- microgram per cubic meter ($\mu\text{g}/\text{m}^3$)
- *parts per million (ppm)*
- *the micron (μ) or preferably, its equivalent, the micrometer (μm).*

Converting $\mu\text{g}/\text{m}^3$ to ppm:

$$\text{ppm} = \frac{\frac{M_p}{GMW} \times 22.414 \times \frac{T_2}{273K} \times \frac{101.325kPa}{P_2}}{V_a \times 1,000L/\text{m}^3} \dots\dots\dots (6)$$

Where, M_p = air pollutant in $\mu\text{g}/\text{m}^3$; GMW = Gram molecular weight; T_2 = temp at which air sample was taken, P_2 = pressure at which air sample was taken; V_a = sample volume in m^3 .

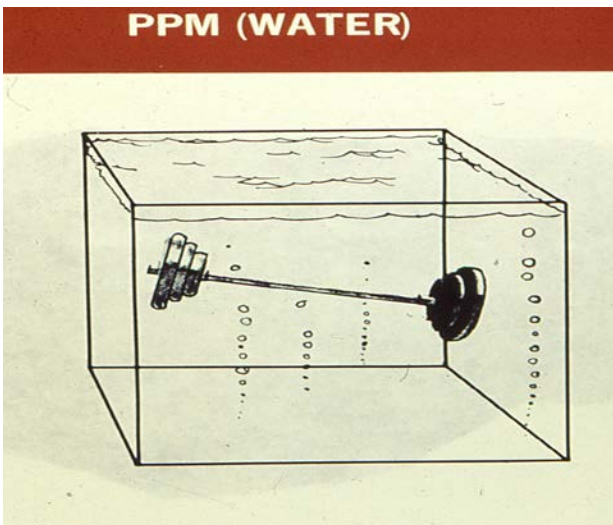


Figure 2: PPM in water is mass to mass ratio

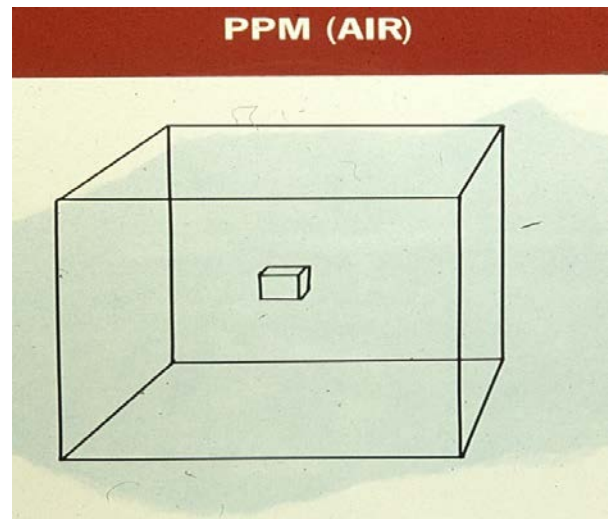


Figure 3: PPM in air is volume to volume ratio

Example 1: A one-cubic-meter sample of air was found to contain $80 \mu\text{g}/\text{m}^3$ of SO_2 . The temperature and pressure were 25°C and 103.193 kPa when the air sample was taken. What was the SO_2 concentration in ppm?

Example 1: Solutions

$$\text{GMW of } \text{SO}_2 = 32.07 + 2(16.00) = 64.07$$

Next, we must convert the temperature to absolute temperature. Thus, $25^\circ\text{C} = 25 + 273 = 298 \text{ K}$.

Using Eq.(6)
$$\text{ppm} = \frac{80 \mu\text{g}/\text{m}^3}{64.07} \times 22.414 \times \frac{298\text{K}}{273\text{K}} \times \frac{101.325\text{kPa}}{103.193\text{kPa}} = 0.030 \text{ ppm of } \text{SO}_2 \text{ Ans.}$$

4. Air Pollution Perspective

Air Pollution is of public health concern on several scales: micro, meso, and macro. Indoor air pollution results from products used in construction materials, adequacy of general ventilation, and geophysical factors that may result in exposure to naturally occurring radioactive materials. Industrial and mobile sources contribute to meso-scale air pollution that contaminates the ambient air that surrounds us outdoors.

Macro-scale impacts include transport of ambient air pollutants over large distances and global impact, for example, acid rain and ozone pollution. Global impacts of air pollution result from

sources that may potentially change the upper atmosphere, for example, depletion of the ozone layer and global warming.

4.1 Criteria Air Pollutants

The Clean Air Act (CAA) requires the USEPA to set National Ambient Air Quality Standards (NAAQS) for six common air pollutants, called “criteria pollutants”, to protect health, the environment, and property. The criteria pollutants are ground-level ozone, particulate matter, lead, nitrogen dioxide, carbon monoxide, and sulfur dioxide. Volatile organic compounds are also monitored, tracked, and controlled to help reduce ozone concentrations in our air, but do not have their own standards. All states are required to meet these standards or develop plans to come into compliance. USEPA calls the pollutants, CO, NO₂, SO₂, PM₁₀, and Particulate Lead primary criteria pollutants and Ozone the secondary criteria pollutant. The data for the six criteria pollutants are monitored by each state and reported to USEPA.



Figure 4: Criteria Pollutant Data Explorer

4.2 Air Pollution Standards

The **1970 Clean Air Act (CAA)** required USEPA to investigate and describe the environmental effects of any air pollutant emitted by stationary or mobile sources that may adversely affect human or the environment. The USEPA used these studies to establish the **NAAQS (Error! Reference source not found.)**. These standards are for the ambient air, that is, the outdoor air that normally surrounds us. Standards are required to "accurately reflect the latest scientific knowledge," and are reviewed every five years by a [Clean Air Scientific Advisory Committee \(CASAC\)](#), consisting of "seven members appointed by the [EPA administrator](#)."²

Table 1: National Ambient Air Quality Standards – NAAQS³

Pollutant	Type	Standard	Averaging Time	Form ^a	Regulatory Citation
Sulfur dioxide (SO ₂)	Primary	75 ppb	1-hour	99th Percentile of 1-hour daily maximum concentrations, averaged over 3 years	40 CFR 50.17a

² Goldstein, Bernard D (2018-12-11). "[The latest chapter in EPA vs environmental science saga](#)". *The Hill*. Retrieved 2018-12-13

³ https://en.wikipedia.org/wiki/National_Ambient_Air_Quality_Standards

	Secondary	0.5 ppm (1,300 $\mu\text{g}/\text{m}^3$)	3-hour	Not to be exceeded more than once per year	40 CFR 50.5a
Particulate matter (PM_{10})	Primary and Secondary	150 $\mu\text{g}/\text{m}^3$	24-hour	Not to be exceeded more than once per year on average over 3 years	40 CFR 50.6a
Fine particulate matter ($\text{PM}_{2.5}$)	Primary	12 $\mu\text{g}/\text{m}^3$	annual	Annual mean, averaged over 3 years	40 CFR 50.18a
	Secondary	15 $\mu\text{g}/\text{m}^3$	annual	Annual mean, averaged over 3 years	40 CFR 50.7a
	Primary and Secondary	35 $\mu\text{g}/\text{m}^3$	24-hour	98th percentile, averaged over 3 years	40 CFR 50.18a
Carbon monoxide (CO)	Primary	35 ppm (40 mg/m^3)	1-hour	Not to be exceeded more than once per year	40 CFR 50.8a(2)
	Primary	9 ppm (10 mg/m^3)	8-hour	Not to be exceeded more than once per year	40 CFR 50.8a(1)
Ozone (O_3)	Primary and Secondary	0.12 ppm (235 $\mu\text{g}/\text{m}^3$)	1-hour ^b	expected number of days per calendar year, with maximum hourly average concentration greater than 0.12 ppm, is equal to or less than 1	40 C.F.R. 50.9a
	Primary and Secondary	0.070 ppm (140 $\mu\text{g}/\text{m}^3$)	8-hour	Annual fourth-highest daily maximum 8-hour concentration, averaged over 3 years	40 CFR 50.19a

Nitrogen dioxide (NO ₂)	Primary and Secondary	0.053 ppm (100 µg/m ³)	annual	Annual mean	40 CFR 50.11a
	Primary	0.100 ppm (188 µg/m ³)	1-hour	98th percentile of 1-hour daily maximum, averaged over 3 years	40 CFR 50.11b
Lead (Pb)	Primary and Secondary	0.15 µg/m ³	Rolling 3 months	Not to be exceeded	40 CFR 50.12a

^aEach standard has its own criteria for how many times it may be exceeded

^bAs of June 15, 2005, the 1-hour ozone standard no longer applies to areas designated with respect to the 8-hour ozone standard (which includes most of the United States, except for portions of 10 states)

The primary standard was established to protect human health with an “adequate margin of safety”. The secondary standards are intended to prevent environmental and property damage. In 1987 USEPA revised the **NAAQS**. The standard for hydrocarbon was dropped and the standards for the Total Suspended Particulates (TSP) was replaced with a particulate standard based on a mass of particulate matter with an aerodynamic diameter $\leq 10 \mu\text{m}$, which is referred to as the PM₁₀ standard.

4.3 Air Quality Region

States are divided into *Air Quality Region* (AQR).

- An AQR that has air quality equal to or better than the primary standard is called an *attainment area*.
- Those area that do not meet the primary standard are called *nonattainment area*.

Under 1970 CAA, EPA was also directed to establish regulations for *hazardous air pollutants* (HAPs) using a risk-based approach. These are called **NESHAPs** – National Emission Standards for Hazardous Air Pollutants. Because EPA had difficulty defining “an ample margin of safety” as required by law, only seven HAPs were regulated between 1970 and 1990: asbestos, arsenic, benzene, beryllium, mercury, vinyl chloride, and radionuclides. The Clean Air Act Amendments (CAAA) of 1990 directed USEPA to establish a HAP emissions control program based on technology for 189 chemicals.

USEPA will establish emission allowances based on *Maximum Achievable Control Technology* (**MACT**) for 174 categories of industrial sources that potentially emit 9.08 megagrams (Mg) (10 tons/year, 1 Mg = 1.1023 short tons) per year of a single HAP or **22.7 Mg** (25 tons/year) per year of combination of HAPs. A **MACT** can include process changes, material substitutions, or air pollution control equipment.

5. Effects of Air Pollutants

Air pollutants can have effects on materials, vegetations, and health. The following sections describe the effects of air pollutants.

5.1 Effect on Materials

The air pollutants can deteriorate the materials with time and decrease the actual life of the materials in use.

Five mechanisms of material deterioration have been attributed to air pollution:

- Abrasion
- Deposition and Removal
- Direct Chemical Attack
- Indirect Chemical Attack
- Electrochemical Corrosion

Solid particles of large enough size and traveling at high enough speed can cause deterioration by **abrasion**. With the exception of soil particles in dust storms and lead particles from automatic weapons fire, most air pollutant particles either are too small or travel at too slow a speed to be abrasive. Small liquid and solid particles that settle on exposed surfaces do not cause more than aesthetic deterioration.

Solubilization and oxidation/reduction reactions typify direct chemical attack. Frequently water must be present as a medium for these reactions to take place. SO_2 and SO_3 in the presence of water react with limestone (CaCO_3) to form CaSO_4 and gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$). Both CaSO_4 and gypsum are more soluble in water than CaCO_3 , and both are leached away when it rains.

Indirect chemical attack occurs when pollutants are absorbed and then react with some component of the absorbent to form a destructive compound. The compound may be destructive because it forms an oxidant, reductant, or solvent. Further, a compound can be destructive by removing an active bond in some lattice structure. For example, leather becomes brittle after it absorbs SO_2 which reacts to form H_2SO_4 because the presence of minute quantities of iron. The iron reacts as a catalyst for the formation of acid.

Oxidation/reduction reaction cause local chemical and physical differences on metal surfaces. These differences, in turn, result in the formation of microscopic anodes and cathodes.

Electrochemical corrosion results from the potential that develops in these microscopic batteries.

Factors that influence deterioration materials are:

- Moisture,
- Temperature,

- Sunlight, and
- Position of the exposed material.

Moisture – in the form of humidity. Material deterioration occurs when humidity > **60%**. Humidity between **70-90%** promotes corrosion without air pollutants.

Temperature – Higher temperature generally results higher reaction rates.

Sunlight – In addition to the oxidation effect of its ultraviolet wave lengths, sunlight stimulates air pollution damage by providing the energy for pollutant formation and cyclic reformation. The cracking of rubber and the fading of dyes have been attributed to ozone produced by these photochemical reactions. More **sunlight** increases rate of deterioration

Position of the exposed material – The position of the exposed surface influences the rate of deterioration by two ways:

- ✓ Whether the surface is vertical or horizontal, or at some angle affects the deposition and wash-off rates.
- ✓ Whether the surface is upper or lower one. When the humidity is sufficient high, the lower side usually deteriorates faster because rain does not remove the pollutants as efficiently.

5.2 Effect on Vegetations

Effect of air pollutants on vegetations can happen and/or be assessed by following ways:

- Cell and leaf anatomy:
- Pollutant damage
- Problems of diagnosis

Cell and leaf anatomy:

- **Cell:** Typical plant cell has 3 main components.
 - The cell wall – much like human skin, it is thin in young plants and gradually thickens with age.
 - The protoplast – is the term used to describe protoplasm of one cell. It consists mainly of water, but also includes protein, fat, and carbohydrates.
 - **The inclusions** – The nucleus contains the hereditary material (DNA), which controls the operation of the cell. The protoplasm located outside of nucleus is cytoplasm. Within the cytoplasm there are tiny bodies or plastids, such as chloroplasts, leucoplasts, and mitochondria. Chloroplasts contain the chlorophyll that manufactures the plant's foods through photosynthesis. Leucoplasts convert starch into starch grain. Chromoplasts are responsible for the red, yellow, and orange colors of the fruit and flowers.

Tree leaves contains 3 primary tissue systems – the epidermis, the mesophyll, and vascular bundle (veins). Chloroplasts are not present in epidermal cells. The opening underside of the leaf is called stoma (*stomata – plural*). The mesophyll, which contains both palisade parenchyma and spongy parenchyma, contains chloroplasts. It is the food production center. The vascular bundles carry water, minerals, and food through the leaf and to and from the main stem of the plant (*Figure 5*).

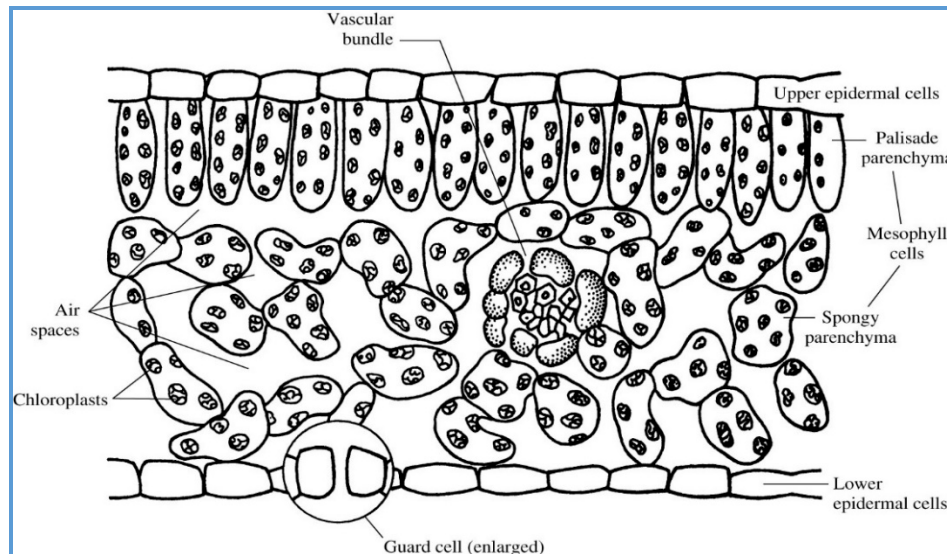


Figure 5: Tree leaf structure

Pollutant damage:

Ozone – injures the palisade cells. The chloroplasts condense and ultimately the cell walls collapse. This results in the formation **red-brown spots and turn white** after few days. The white spot is called **fleck**. Ozone injury appears to be the greatest during midday on sunny days. The guard cells are more likely to be open under these conditions and thus allow pollutants to enter the leaf. Some examples of Ozone damages are shown in *Figure 6*, *Figure 7*, and *Figure 8*.



Figure 6: Ozone damage to radish plant resulting in smaller radish



Figure 7: Ozone damage to romaine lettuce – silver shine reduces value



Figure 8: Ozone damage to alfalfa – reduces nutritional value as animal forage

NO₂ – plant growth may be inhibited by continuous exposure to 0.5 ppm. Levels in excess of 2.5 ppm for periods of 4 hours or more required to produce *nercosis* (surface spotting due to plasmolysis or loss of protoplasm).

SO₂ – SO₂ injury is also typified by *nercosis*, but much lower levels. A concentration of 0.3 ppm for 8 hours is sufficient. Lower levels for longer periods of exposure will produce a diffuse *chlorosis* (bleaching). Some examples of SO₂ damages are shown in *Figure 9* and *Figure 10*.

Fluoride deposition on plants not only causes them damage but may result in a second outward effect. Grazing animals may accumulate an excess of fluoride that mottles their teeth and ultimately them to fall out.

Problems of diagnosis:

Droughts, insects, diseases, herbicides overdose, and nutrient deficiencies all can cause injury that resemble air pollutant damage. Also, combinations of pollutants that alone cause no damage are known to produce acute effects when combined. This effect is known as *synergism*.



Figure 9: Gross sulfur dioxide damage to trees



Figure 10: Sulfur dioxide damage to corn

5.3 Effect on Health

The health effects caused by air pollution may include difficulty in breathing, wheezing, coughing, [asthma](#) and worsening of existing respiratory and cardiac conditions. These effects can result in increased medication use, increased doctor or [emergency department](#) visits, more hospital admissions and premature death. The human health effects of poor air quality are far reaching, but principally affect the body's respiratory system and the cardiovascular system. Individual reactions to air pollutants depend on the type of pollutant a person is exposed to, the degree of exposure, and the individual's health status and genetics.⁴ The most common sources of air pollution include particulates, ozone, nitrogen dioxide, and sulfur dioxide. Children aged less than five years that live in developing countries are the most vulnerable population in terms of total deaths attributable to indoor and outdoor air pollution.⁵

- **Effects on Health – Acute health effect**
 - Short time
 - Intense irritation
- **Effects on Health – Chronic health effect**
 - Long time
 - Moderate irritation
- **Inhalation and retention of particles:**
 - The degree of penetration of particles into the lower respiratory tract (LRT) is primarily a function of the size of the particles and the rate of breathing.
 - Particles > 5 to $10 \mu\text{m}$ are screened out by the hairs in the nose. Sneezing also helps the screening process.
 - Particles in the 1 to $2 \mu\text{m}$ size range penetrate to alveoli. These particles are small enough to bypass screening and deposition in the upper respiratory tract (URT), however they are big enough that their terminal settling velocity allows them to deposit where they can do the most damage.
 - Particles that are $0.5 \mu\text{m}$ in diameter do not have enough terminal settling velocity to be removed efficiently.
- **Chronic respiratory disease:**
 - Several long-term diseases of the respiratory system are seriously aggravated by and perhaps may cause by air pollutants.
 - Airway resistance is the narrowing of air passages because of the presence of the irritating substances.
 - The result is that breathing becomes difficult. Bronchial asthma is a form of airway resistance that results from the **allergy**.

⁴ Daniel A. Vallero. "[Fundamentals of Air Pollution](#)". Elsevier Academic Press

⁵ [Air quality and health](#). *Who.int*. Retrieved 2011-11-26

- Chronic bronchitis is currently defined to be present in a person when excess **mucus** in bronchioles results in a cough for 3 months a year for two consecutive years.
- Lung infections, tumors, and heart disease must be absent.
- Cancer of the bronchus (**lung cancer**) is characterized by abnormal, disorderly new cell growth originating in the bronchial mucous membrane.

Carbon monoxide (CO):

This colorless, odorless gas is lethal to humans within a few minutes at concentrations exceeding 5,000 ppm. CO reacts with hemoglobin in the blood to form carboxyhemoglobin (COHb). Hemoglobin has a greater affinity for CO than oxygen. Thus, formation of COHb effectively deprives the body of oxygen. At COHb levels 5 to 10%, visual perception, manual dexterity, and ability to learn are impaired. A concentration of 50 ppm of CO for 8 hours will result in a COHb level of about 7.5%. At COHb levels 2.5 to 3%, people with heart disease are not able to perform certain exercise as well as they might in the absence of COHb. A concentration of 20 ppm of CO for 8 hours will result in a COHb level of about 2.8%. The sensitive people are those with heart and circulatory ailments, chronic pulmonary disease, developing fetuses, and those with conditions that cause increased oxygen demand, such as fever.

Hazardous Air Pollutants (HAPs):

Most of the information on the direct human health effects of HAPs (*also known as air toxics*) comes from studies of industrial workers. Exposure to air toxics in the workplace is generally much higher than in the ambient air. The HAPs regulated under National Emission Standards for Hazardous Air Pollutants (NESHAP) program are identified as casual agents for a variety of diseases, for instance **asbestos, arsenic, benzene, coke oven emission, and radionuclides** may cause cancer. **Beryllium** primarily causes lung disease but also affects the **liver, spleen, kidneys, and lymph glands**. **Mercury attacks the brain, kidneys, and bowels**. Other potential effects from the HAPs are birth defects and damage to the immune and nervous systems.

Lead (Pb):

Lead is an accumulative poison. Lead is ingested in food and water, as well as being inhaled. Of that portion taken by ingestion, approx. 5-10% is absorbed in the body. Between 20–50% of the inspired portion is absorbed. Unabsorbed portion are excreted in the feces and urine. **Lead** is measure in the urine and blood for diagnostic evidence of lead poisoning. **Pb** levels in blood in excess of 80 µg/100 g result in constipation and abdominal cramps. When an acute exposure results in blood levels of **Pb** > 120 µg/100 g, **acute brain damage** (encephalopathy) may result. Such acute exposure results in convulsions, coma, cardiorespiratory arrest, and death. Acute exposure may occur over a period of 1 to 3 weeks. Chronic exposure to **Pb** may result in **brain damage** characterized by **seizures, mental incompetence, and active aggressive behavior**. Weakness of extensor muscles of hands and feet and eventual paralysis may also result. Atmospheric **lead** occurs as a particulate. The particle size range is between 0.16 to 0.43 µm.

Nitrogen dioxide (NO₂):

Exposure to NO₂ concentrations above 5 ppm for 15 minutes results in **cough** and **irritation** of the respiratory tract. Continued exposure may produce an abnormal accumulation of fluid in lung (*pulmonary edema*). NO₂ gas is reddish brown in concentrated form and gives a brownish yellow tint at lower concentrations. At 5 ppm, it has a pungent sweetish odor. The average concentration of NO₂ in tobacco smoke is about 5 ppm.

Photochemical oxidants:

Although photochemical oxidants include peroxyacetyl nitrate (PAN), acrolein, peroxybenzoyl nitrates (PBzN), and nitrogen oxides, the major oxidant is ozone (O₃). Ozone is commonly used as an indicator of the total amount of oxidant present. Oxidant concentrations above 0.1 ppm result eye irritation. At concentration of 0.3 ppm, cough and chest discomfort are increased. Those people who suffer from chronic respiratory disease are particularly susceptible.

PM₁₀:

Since large particles are not inhaled deeply into the lung, this is why EPA switched from an air quality standard based on total suspended matter to one based on particles with aerodynamic diameter (*The aerodynamic diameter of an irregular particle is defined as the diameter of the spherical particle with a density of 1,000 kg/m³ and the same settling velocity as the irregular particle*) < 10 μm. Higher levels of PM₁₀ increase risk of respiratory, **cardiovascular**, and **cancer related deaths**, as well as, **pneumonia**, **lung function loss**, and **asthma**. Recent studies have pointed toward particle size < 2.5 μm as a major contributor to elevated death rates in polluted cities. However, a suitable biological mechanism to explain what causes the deaths is lacking. Nonetheless, in order to provide an “adequate margin of safety” the EPA administrator proposed a new standard based on **PM_{2.5}** in July 1997.

Sulfur oxides (SO_x) and total suspended particulates (TSP):

The sulfur oxides include sulfur dioxide (SO₂), sulfur trioxide (SO₃), their acids, and the salts of their acids. Rather than separating the effects of SO₂ and SO₃, they are usually treated together although there is a speculation that a definite synergism exists whereby fine particulates carry absorbed SO₂ to lower respiratory tract (LRT). The SO₂ in the absence of particulates would be absorbed in the mucous membranes of the upper respiratory tract (URT). Patients suffering from chronic bronchitis have shown an increase in respiratory symptoms when the TSP levels exceeded 350 μg/m³ and SO₂ level was above 0.095 ppm. Studies in Holland at an interval of 3 years showed that pulmonary function improved as SO₂ and TSP levels drop from 0.10 ppm and 230 μg/m³ to 0.03 ppm and 80 μg/m³, respectively.

Air pollution episodes:

Air pollution disaster (called episodes). The world's worst short-term civilian pollution crisis was the 1984 Bhopal Disaster in India.⁶ Leaked industrial vapours from the Union Carbide factory, belonging to Union Carbide, Inc., U.S.A. (later bought by Dow Chemical Company), killed at least 3787 people and injured from 150,000 to 600,000. The United Kingdom suffered its worst air

⁶ Simi Chakrabarti. "20th anniversary of world's worst industrial disaster". [Australian Broadcasting Corporation](#)

pollution event when the December 4 Great Smog of 1952 formed over London. In six days more than 4,000 died and more recent estimates put the figure at nearer 12,000.⁷ An accidental leak of anthrax spores from a biological warfare laboratory in the former USSR in 1979 near Sverdlovsk is believed to have caused at least 64 deaths.⁸ The worst single incident of air pollution to occur in the US occurred in Donora, Pennsylvania in late October, 1948, when 20 people died and over 7,000 were injured.⁹ The World Health Organization estimated in 2014 that every year air pollution causes the premature death of some 7 million people worldwide. Studies published in March 2019 indicated that the number may be around 8.8 million.¹⁰ The USEPA has estimated that limiting ground-level ozone concentration to 65 parts per billion, would avert 1,700 to 5,100 premature deaths nationwide in 2020 compared with the 75-ppb standard. The agency projected the more protective standard would also prevent an additional 26,000 cases of aggravated asthma, and more than a million cases of missed work or school. Following this assessment, the USEPA acted to protect public health by lowering the National Ambient Air Quality Standards (NAAQS) for ground-level ozone to 70 parts per billion (ppb).¹¹

Air pollution costs the world economy \$5 trillion per year as a result of productivity losses and degraded quality of life, according to a joint study by the World Bank and the Institute for Health Metrics and Evaluation (IHME) at the University of Washington. These productivity losses are caused by deaths due to diseases caused by air pollution. One out of ten deaths in 2013 was caused by diseases associated with air pollution and the problem is getting worse. The problem is even more acute in the developing world. Children under age 5 in lower-income countries are more than 60 times as likely to die from exposure to air pollution as children in high-income countries. The report states that additional economic losses caused by air pollution, including health costs and the adverse effect on agricultural and other productivity were not calculated in the report, and thus the actual costs to the world economy are far higher than \$5 trillion.¹²

6. Origin and Fate of Air Pollutants

6.1 Carbon Monoxide (CO)

Incomplete oxidation of carbon results in the production of CO. The natural anaerobic decomposition of carbonaceous material by soil microorganisms release approximately 9×10^{15} moles of methane (CH₄) to atmosphere each year. The natural formation of CO results from an intermediate step in the oxidation of methane. The hydroxyl radical (OH·) serves as the initial oxidizing agent. It combines with CH₄ to form an alkyl radical:

⁷ Bell, Michelle L.; Michelle L. Bell; Devra L. Davis; Tony Fletcher (January 2004). "A Retrospective Assessment of Mortality from the London Smog Episode of 1952: The Role of Influenza and Pollution". *Environ Health Perspect.* **112** (1): 6–8. doi:10.1289/ehp.6539. PMC 1241789. PMID 14698923. S2CID 13045119

⁸ Meselson M, Guillemin J, Hugh-Jones M, et al. (November 1994). "The Sverdlovsk anthrax outbreak of 1979" (PDF). *Science.* **266** (5188): 1202–08. Bibcode:1994Sci...266.1202M. doi:10.1126/science.7973702. PMID 7973702. Archived from the original (PDF) on 2006-09-21

⁹ Davis, Devra (2002). *When Smoke Ran Like Water: Tales of Environmental Deception and the Battle Against Pollution*. Basic Books. ISBN 978-0-465-01521-4

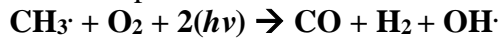
¹⁰ https://en.wikipedia.org/wiki/Air_pollution

¹¹ https://en.wikipedia.org/wiki/Air_pollution

¹² https://en.wikipedia.org/wiki/Air_pollution



after 39 series of complex reactions



Anthropogenic source (those associated with the activities of human beings) includes motor vehicles, fossil fuel burning for electricity and heat, industrial processes, solid waste disposal, and miscellaneous burning of such things as leaves and brush. Approximately 1×10^{13} moles of CO are released by these sources each year, about 60% of it comes from motor vehicle emissions. No significant change in the global atmospheric CO level has been observed over the past 20 years.

6.2 Hazardous Air Pollutants (HAPs)

The EPA has identified 166 categories of major sources and 8 categories of area sources for the 189 HAPs listed in literature. The source categories represent a wide range of industrial groups, such as:

Table 2: HAPS Sources

Fuel combustion	Metal processing
Petroleum & natural gas production and refining	Surface coating processes
Waste treatment & disposal processes	Agricultural chemical productions
Ploymers and resins productions	

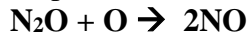
There are also a number of miscellaneous source categories, such as *dry cleaning* and *electroplating*. In addition to these direct emissions, air toxics can result from chemical formation reactions in the atmosphere. These reactions involve chemicals emitted to the atmosphere that are not listed HAPs and may not be toxic themselves but can undergo atmospheric transformations to generate HAPs.

6.3 Lead

Volcanic activity and airborne soil are the primary sources of atmospheric lead. Smelters and refining processes, as well as incineration of lead-containing wastes, are major sources of lead. Approximately 70-80% of lead which used to be added to gasoline was discarded to the atmosphere. Submicron lead particles, which are formed by volatilization and subsequent condensation, attach to larger particles or they form nuclei before they are removed from the atmosphere. Once they have attained a size of several microns, they either settle out or are washed out by rain.

6.3 Nitrogen Dioxide (NO₂)

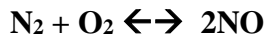
Bacterial action in the soil releases nitrous oxide (N₂O) to the atmosphere. In the upper troposphere and stratosphere, atomic oxygen reacts with the nitrous oxide to form nitric oxide (NO).



The atomic oxygen results from the dissociation of ozone. The nitric oxide further reacts with ozone to form nitrogen dioxide (NO₂).



The global formation of NO₂ by this process is estimated to be 0.45 Pg (Peta gram, 10¹⁵) annually. Combustion processes account for 96% of the anthropogenic sources of nitrogen dioxide. Nitrogen and oxygen coexist in the atmosphere w/o reaction, but at high temperatures in excess of 1,600 K, they react:



If the combustion gas is rapidly cooled after the reaction by exhausting it releases to the atmosphere, the reaction is quenched, and NO is the byproduct. The NO in turn reacts with ozone or oxygen to form NO₂. The anthropogenic contribution to global emission NO₂ by this route amounted to 0.48 Tg (Tera gram, 10¹²) in 1965. Ultimately, the NO₂ is converted to NO₂⁻ or NO₃⁻ in particulate form and these particulates are then washed out by precipitation. The dissolution of nitrate in a droplet allows for the formation of nitric acid (HNO₃). This, in part, accounts for “acid” rain found downwind of industrialized areas.

6.4 Photochemical Oxidants

Unlike the other pollutants, photochemical oxidants result entirely from atmospheric reactions and are not directly attributable to either people or nature. They are called *secondary pollutants*. They are formed from series of reactions that are initiated by the absorption of a photon by an atom, molecule, free radical, or ion. Ozone is the principal photochemical oxidant. Its formation is usually attributed to the nitrogen photolytic cycle. Hydrocarbons modify this cycle by reacting with atomic oxygen to form free radicals (highly reactive organic species). The hydrocarbons, nitrogen oxides, and ozone react and interact to produce more nitrogen dioxide and ozone. The whole reaction sequence depends on an abundance of sunshine. A result of these reactions is the photochemical “smog” for which Los Angeles is famous.

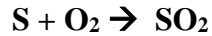
6.5 Sulfur Oxides

Sulfur oxides may be both primary and secondary pollutants. Power plants, industry, volcanoes, and the oceans emit SO₂, SO₃, and SO₄²⁻ directly as primary pollutants. Biological decay processes and some industrial sources emit H₂S, which is oxidized to form secondary pollutant SO₂. In terms of sulfur, approx. 0.125 Pg (Peta gram, 10¹⁵) are emitted annually by natural sources. Approximately 0.45 Tg (Tera gram, 10¹²) of sulfur may be attributed to anthropogenic sources each year.

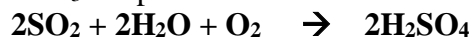
The most important oxidizing reaction for H₂S appears to be one involving ozone:



The combustion fossil fuels containing sulfur yields sulfur dioxide in direct proportion to the sulfur content of the fuel:



This reaction implies that for each gram of sulfur in the fuel, 2 grams of SO_2 are emitted to the atmosphere. Since combustion process is not 100% efficient, generally 5% sulfur is assumed to be as ash, that is, 1.90 grams SO_2 per gram of sulfur is emitted. The ultimate fate of most of the SO_2 in the atmosphere is conversion to sulfate salts, which are removed by sedimentation or by wash out with precipitation. The conversion of sulfate is by either of two routes: *catalytic oxidation* or *photochemical oxidation*. The first process is most effective if water droplets containing Fe^{3+} , Mn^{2+} , or NH_3 are present.

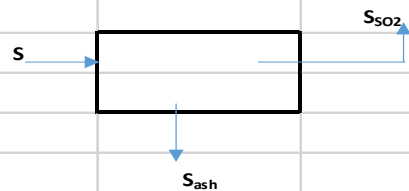


At low relative humidity, the primary conversion process is photochemical oxidation.

Example 2: An Illinois coal is burned at a rate of 1.25 kg/s. If the analysis of the coal reveals a sulfur content of 3.0%, what is the annual rate of emission? Assume sulfur in the ash is 4.5% of the input sulfur.

Example 2: Solutions

Given					
Coal burn rate =	1.25	kg/s			
Sulfur content in coal =	3.0%				
Sulfur content in ash =	4.5%				
Coal burn per year =	1.25 kg/s x 86,400 s /d x 365 d/yr				
=	39420000	kg/yr			Mass balance diagram
Sulfur generated per year, S =	39420000 kg/yr. x 0.03				Mass balance equation, S = S _{SO2} + S _{ash}
	1182600	kg/yr			
Ash generated per year, S _{ash} =	1182600 x 0.045				
	53217	kg			
From mass balance equation, S _{SO2}	S - S _{ash}				
	= 1182600 - 53217				
	1129383	kg/yr			
From this reaction equation	S	+	O ₂	=	SO ₂ .
	32.07		16 x 2		32.07 + 16x2
	32.07		32		64.07
∴ S _{SO2} =	1129383 x (64.07/32.07)				
	2256300.867	kg/yr			ANS.



6.6 Particulates

Sea salt, soil dust, volcanic particles, and smoke from forest fires account for 1.404 Pg particulate emissions each year. **Anthropogenic** emissions from fossil fuel burning and industrial processes account for emissions of 92 Tg per year. Secondary sources of particulates include the conversion of H₂S, SO₂, NO_x, NH₃, and hydrocarbons.

H₂S and SO₂ are converted to sulfate. NO_x and NH₃ are converted to nitrates. Natural sources of secondary pollutants yield about 1.099 Pg annually. Anthropogenic sources yield about 0.204 Pg annually.

6.7 Ozone

Ozone or **trioxygen**, is an inorganic molecule with the chemical formula **O₃**. It is a pale blue gas with a distinctively pungent smell. It is an allotrope of oxygen that is much less stable than the diatomic allotrope O₂, breaking down in the lower atmosphere to O₂ (dioxygen). Ozone is formed from dioxygen by the action of ultraviolet (UV) light and electrical discharges within the Earth's atmosphere (Figure 11). It is present in very low concentrations throughout the latter, with its highest concentration high in the ozone layer of the stratosphere, which absorbs most of the Sun's ultraviolet (UV) radiation.

Ozone's odor is reminiscent of chlorine, and detectable by many people at concentrations of as little as 0.1 ppm in air. Ozone's O_3 structure was determined in 1865. The molecule was later proven to have a bent structure and to be diamagnetic. In standard conditions, ozone is a pale blue gas that condenses at progressively cryogenic temperatures to a dark blue liquid and finally a violet-black solid. Ozone's instability with regard to more common dioxygen is such that both concentrated gas and liquid ozone may decompose explosively at elevated temperatures or fast warming to the boiling point. It is therefore used commercially only in low concentrations.

Ozone is a powerful oxidant (far more so than dioxygen) and has many industrial and consumer applications related to oxidation. This same high oxidizing potential, however, causes ozone to damage mucous and respiratory tissues in animals, and also tissues in plants, above concentrations of about 0.1 ppm. While this makes ozone a potent respiratory hazard and pollutant near ground level, a higher concentration in the ozone layer (from two to eight ppm) is beneficial, preventing damaging UV light from reaching the Earth's surface.



Figure 11: Atmosphere showing the location of ozone layer

7. Micro and Macro Air Pollution

Air pollution problems may occur on 3 scales: *micro*, *meso*, and *macro*.

- Micro-scale problems range from those covering less than a cm to those the size of a house or slightly larger.
- Meso-scale air pollution problems are those of a few hectares up to size of a city or county.
- Macro-scale problems extended from counties to states, nations, and in the broadest sense, the globe.

Micro and macro-scale are:

- a. Indoor Air Pollution

- b. Acid Rain
- c. Ozone Depletion
- d. Greenhouse Effect/Global Warming

7.1 Indoor Air Pollution

A lack of ventilation indoors concentrates air pollution where people often spend the majority of their time. Radon (Rn) gas, a carcinogen, is exuded from the Earth in certain locations and trapped inside houses. Building materials including carpeting and plywood emit formaldehyde (H₂CO) gas. Paint and solvents give off volatile organic compounds (VOCs) as they dry. Lead paint can degenerate into dust and be inhaled. Intentional air pollution is introduced with the use of air fresheners, incense, and other scented items. Controlled wood fires in stoves and fireplaces can add significant amounts of smoke particulates into the air, inside and out.¹³ Indoor pollution fatalities may be caused by using pesticides and other chemical sprays indoors without proper ventilation.

Carbon monoxide poisoning and fatalities are often caused by faulty vents and chimneys, or by the burning of charcoal indoors or in a confined space, such as a tent.¹⁴ Chronic carbon monoxide poisoning can result even from poorly-adjusted pilot lights. Traps are built into all domestic plumbing to keep sewer gas and hydrogen sulfide, out of interiors. Clothing emits tetrachloroethylene, or other dry cleaning fluids, for days after dry cleaning.

Though its use has now been banned in many countries, the extensive use of asbestos in industrial and domestic environments in the past has left a potentially very dangerous material in many localities. Asbestosis is a chronic inflammatory medical condition affecting the tissue of the lungs. It occurs after long-term, heavy exposure to asbestos from asbestos-containing materials in structures. Sufferers have severe dyspnea (shortness of breath) and are at an increased risk regarding several different types of lung cancer. As clear explanations are not always stressed in non-technical literature, care should be taken to distinguish between several forms of relevant diseases. According to the World Health Organization (WHO), these may be defined as; asbestosis, *lung cancer*, and *Peritoneal Mesothelioma* (generally a very rare form of cancer, when more widespread it is almost always associated with prolonged exposure to asbestos).

Biological sources of air pollution are also found indoors, as gases and airborne particulates. Pets produce dander, people produce dust from minute skin flakes and decomposed hair, dust mites in bedding, carpeting and furniture produce enzymes and micrometer-sized fecal droppings, inhabitants emit methane, mold forms on walls and generates mycotoxins and spores, air conditioning systems can incubate Legionnaires' disease and mold, and houseplants, soil and surrounding gardens can produce pollen, dust, and mold. Indoors, the lack of air circulation allows these airborne pollutants to accumulate more than they would otherwise occur in nature.

¹³ Duflo, Esther; Greenstone, Michael; Hanna, Rema (2008-11-26). "[Indoor air pollution, health and economic well-being](#)". *S.A.P.I.E.N.S.* **1** (1). Retrieved 2010-08-29

¹⁴ "[Bucknell tent death: Hannah Thomas-Jones died from carbon monoxide poisoning](#)". BBC News. 17 January 2013. Retrieved 22 September 2015

People in cold climates may spend 70-80% of time indoors. Research shows that indoor air may be more polluted than the outdoor air. CO from improperly operating furnaces has long been a serious concern, for instance, people have even died. More recently, chronic low levels of CO pollution have been recognized as a result of death. Gas ranges, ovens, pilot lights, gas and kerosene space heaters, and cigarettes smoke all contribute. NO₂ levels have been found to range 70 µg/m³ in air-conditioned houses with electric ranges to 182 µg/m³ in non-air-conditioned houses with gas stoves. SO₂ levels were found to be very low in houses investigated. On the other hand, respirable particulate matter (**RSP**) was found to increase with one smoker and rise dramatically with two. Radon is not regulated as an ambient air pollutant but has been found in dwellings at alarmingly high concentrations.

Over 300 VOCs have been identified in indoor air. Aldehydes, alkanes, ethers, ketone, and polynuclear aromatic hydrocarbons (**PAHs**) are among them. Formaldehyde (CH₂O) has been singled out as one of the more prevalent, as well as one of the more toxic, compounds. In one study, CH₂O concentrations ranged from 0.0455 ppm to 0.19 ppm.

7.2 Other Air Pollution

Other air pollution could be acid rain, global warming/greenhouse effect and ozone depletion. These are discussed and elaborated under Section titled Contemporary issues.

8. Contemporary Issues

8.1 Acid Rain

Unpolluted rain is naturally acidic because CO₂ from the atmosphere dissolves to a sufficient extent to form carbonic acid. The equilibrium pH for pure rainwater is about 5.6. In USA and Europe pH found to be even lower. Chemical reactions in the atmosphere convert SO₂, NO_x, and VOCs to acidic compounds and associated oxidants and hence pH of the rainwater goes down.

8.2 Global Warming/Greenhouse Effect

Unlike ozone, CO₂ is relatively transparent to shortwave UV light from the sun, and it does absorb and emit longwave radiation at wavelengths typical of the earth and the atmosphere. CO₂ acts much like the glass on a greenhouse. It lets the shortwave radiation from the sun that heats the ground surface but restricts the loss of heat by radiation from the ground surface. The more CO₂ in the atmosphere, the more effective it is in restricting the outflow of radiative energy. Mauna Loa in HI, **1958**, CO₂ levels = 315 – 350 ppm.

Ice cores in Greenland and Antarctica – about 280 ppm. Ice core records show that over the last 160,000 years, no fluctuations of CO₂ have been larger than 70 ppm. Other gases have been

recognized as contributing to the greenhouse effect. Methane (CH₄), nitrous oxide (N₂O), and CFCs are similar to CO₂ in their radiative behavior. Even though their concentrations are much lower than CO₂, these gases are now estimated to trap about 60% as much longwave radiation as CO₂.

In 1989-90, methane in atmosphere was increasing at a rate of 10 or 11 ppb per year. In 1992, it decreased abruptly to about 2 ppb. CO₂ added to the atmosphere comes from the combustion of fossil fuel. Plants take CO₂ for photosynthesis, commonly referred to as a sink. A rapidly growing rain forest can uptake about 1-2 kg/year of carbon per square meter of ground surface.

Attempts to understand the consequence of global warming are based on mathematical models of global circulation of the atmosphere and the oceans. To date the models, have a “good news - bad news” conclusion. Based on a 2° to 6°C rise in global temperature, the following good news is predicted for North America:

- A decrease in heating costs of up to 25%.
- A longer growing season for crops.
- Much easier navigation in the Arctic seas.

The bad news:

- Dried crop conditions in the Midwest and Great Plains, requiring more irrigation.
- Widespread melting of permanently frozen ground with adverse effects on building technology in Alaska and northern Canada.
- A rise in sea level from 0.5 – 1.5 m.

8.3 Ozone Depletion

Without ozone, every living thing in the earth’s surface would be incinerated, although on the other hand, ozone can be lethal. The presence of ozone in the upper atmosphere (20-30 km and up) provides a barrier to ultraviolet (UV) radiation. Too much *UV* can cause skin cancer. Although oxygen also serves as a barrier to UV radiation, it absorbs only over a narrow band centered at a wavelength of **0.2 μm**.

The chlorofluorocarbons (CF₂Cl₂ and CFCl₃ – abbreviated as CFC), which are used as aerosol propellants and refrigerants, react with ozone. The series of reactions occur that create chlorine atom which removes ozone from the system, and that the chlorine atom is continually recycled to remove more ozone to oxygen. It is noted that one Cl atom can break about 100,000 of ozone molecules

9. Effects of Engineering Solutions

Couple of contemporary issues we learned in this topic such as ozone depletion and greenhouse effect are responsible for environmental pollution that has global implication as this can affect other territories/countries. Several anthropogenic activities can generate greenhouse gases (GHGs) that can affect the global warming. As we have learned, water and wastewater treatment plants generate sludge from several process trains and the sludge are digested aerobically and anaerobically depending on the process used in treatment and management of sludge. Depending on the type of sludge digestion process, CH₄ and CO₂ gases are generated that are considered as air pollutant and GHGs. CH₄ gas is highly flammable and its LEL is 5% and UEL is 15% by volume in the air. Any engineering solutions that can reduce the GHGs generation and emission will reduce the global warming. The CH₄ gas can be captured and burned to heat houses or offices or just burned with a flare to reduce the concentration in air and/or can be refined and used to generate electricity. These engineering solutions of air pollution by CH₄ has a global effect as it cannot pass to another territory/country to increase the GHGs. This is also an environmental impact as this engineering solution keeps the air clean. The capturing and using of CH₄ gas to generate electricity create employment which seems to be a great societal and economic impact. So, the broad education for civil/environmental engineering discipline is necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context.

10. Air Pollution Meteorology

Atmospheric conditions which affect air pollution are:

1. Wind direction and speed
2. Cloud cover ® radiation reaching earth ® temperature profile ® turbulence
3. Precipitation
4. The Atmospheric Engine
5. Turbulence
6. Stability
7. Terrain Effects

10.1 Atmospheric Engine

The atmosphere is somewhat like an engine. It is continually expanding and compressing gases, exchanging heat, and generally raising chaos. The driving energy for this engine comes from the sun. The difference in heat input between the equator and the poles provide the initial overall circulation of the earth's atmosphere. The rotation of the earth coupled with the different heat conductivities of the oceans and land produce weather.

Highs and lows:

Because air has mass, it also exerts pressure on things under it. Like water, which exerts greater pressure at greater depth, the atmosphere exerts more pressure at the surface than it does at higher

elevations. The **highs** and **lows** depicted on weather maps are simply areas of **greater** and **lesser pressure**. The elliptical lines showed in the weather maps represent the lines of **constant pressure, or isobars**. The wind flows from the higher areas to lower pressure areas. On the non-rotating planet, the wind direction would be perpendicular to the isobars. Since the earth rotates, an angular thrust called the *Coriolis* effect is added to this motion. The resultant wind direction in the northern hemisphere is show in the figure. The technical names given to these systems are *anticyclones* for highs and *cyclones* for lows. Anticyclones are associated with good weather and cycles are with foul/bad weather.

Tornadoes and hurricanes are the foulest of the cyclones (*Figure 12*). Wind speed is a function of the steepness of the pressure surface. When the isobars are close together, the pressure gradient (slope) is said to be steep and the wind speed is relatively highly. If the isobars are well spread out, the winds are light or nonexistent.



Hurricane vs Tornado

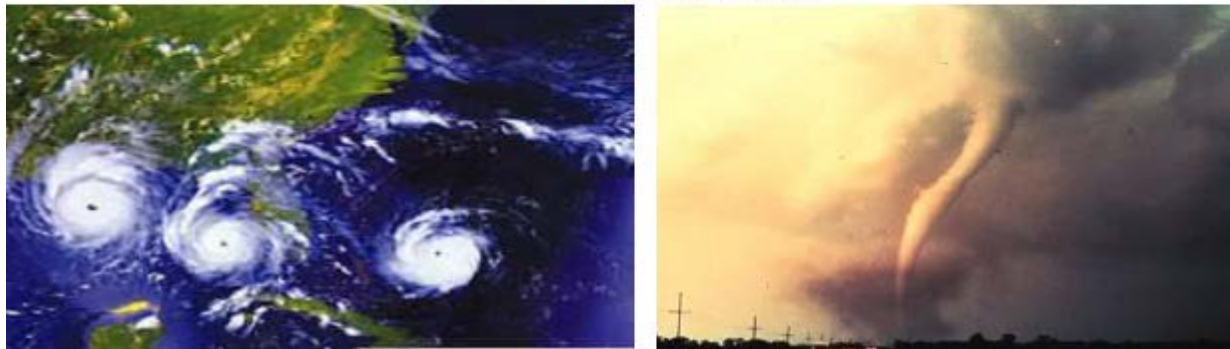


Figure 12: Pictorial view of Hurricane and Tornado

Hurricane is a type of tropical [cyclone](#) with sustained winds that exceed 74 mph and accompanied by **rain, thunder and lightning**.

Tornado is defined in the dictionary as "*a rotating column of air ranging in width from a few yards to more than a mile and whirling at destructively high speeds, usually accompanied by a funnel-shaped downward extension of a cumulonimbus cloud*".

The wind speeds of tornadoes range from 40 mph to 110 mph, span about 75 m across and can travel a few miles. In extreme cases, tornadoes have also reached a speed of 300 mph. A comparative chart is provided in *Table 3*.

Table 3: Comparison of Hurricane and Tornado

	Hurricane	Tornado
About	A hurricane is a cyclone that is located in the North Atlantic Ocean, or the NE Pacific Ocean east of the International Date Line, or the South Pacific Ocean east of 160E, and with sustained winds that reach or exceed 74 mph.	A tornado is a rotating column of air ranging in width from a few yards to more than a mile and whirling at destructively high speeds, usually accompanied by a funnel-shaped downward extension of a cumulonimbus cloud. Winds 40-300+ mph.
Rotation	Clockwise in the southern hemisphere and counterclockwise in the northern hemisphere	Clockwise in the southern hemisphere and counterclockwise in the northern hemisphere
Intensity	Hurricanes are classified into five categories according to the Saffir-Simpson Hurricane Wind Scale. The wind speed and intensity of damage increases as from category 1 to category 5.	The scale used for rating the strength of tornadoes is called the Fujita (F), Enhanced Fujita (EF), and TORRO (T) Scale.
Location	North Atlantic Ocean, the Northeast Pacific Ocean east of the International Date Line, or the South Pacific Ocean east of 160E. Hurricanes are found near the tropical zone, over warm waters in the Atlantic and Pacific ocean.	Tornados have been spotted in all continents except Antarctica. http://www.diffen.com/difference/Hurricane_vs_Tornado

10.2 Turbulence

There are two types of turbulence: Mechanical and Thermal.

Mechanical Turbulence:

It happens due to random fluctuations of wind velocity to the overall average velocity. The fluctuations are caused by the fact that the atmosphere is being sheared and the shearing results from the fact that the wind speed is zero at the ground surface and rises with elevation to near the speed imposed by the pressure gradient. The shearing results in a tumbling, tearing motion as the mass just above the surface fall over the slower moving air at the surface.

The swirls thus formed is called *eddies*. These small eddies feed larger ones. The greater the mean wind speed, the greater the mechanical turbulence. The more mechanical turbulence, the easier it is to disperse and spread atmospheric pollutants.

Thermal Turbulence:

Heating of the ground surface causes turbulence in the same fashion that heating the bottom of a beaker full of water causes turbulence. If the earth's surface is heated strongly and in turns heats the air above it, thermal turbulence will be generated.

10.3 Stability

The tendency of the atmosphere to resist or enhance vertical motion is termed as *stability*. It is related to both wind speed and the change in air temperature with height (*lapse rate*).

There are 3 stability categories:

- **Neutral** – When thermal structure neither enhances nor resist mechanical turbulence.
- **Unstable** – when the mechanical turbulence is enhanced by thermal structure. Cyclones are associated with unstable air.
- **Stable** – when the thermal structure inhibits mechanical turbulence. Anticyclones are associated with stable air.

Definition of related terms and features.

- **Adiabatic process** – a process without addition or loss of heat.
- **Dry adiabatic lapse rate** – The rate at which temperature decrease ($dT/dZ = -1.00^{\circ}C/100m$). It is denoted by the Greek letter gamma, $\dot{\Gamma}$.
- **Superadiabatic lapse rate** – If the temperature of the atmosphere falls at a rate $> \dot{\Gamma}$, the rate is said to be *superadiabatic*.
- **Subadiabatic lapse rate** – If the temperature of the atmosphere falls at a rate $< \dot{\Gamma}$, the rate is called *subadiabatic*. Two cases of *subadiabatic* lapse rate.
- When there is no change in temperature with elevation, the lapse rate is called *isothermal*.
- When the temperature increases with elevation, the lapse rate is called *inversion* (*Figure 13*). Inversion is the most severe form of a stable temperature profile. It is often associated with restricted air volumes that cause air pollution episodes.
- **Plume types** – The smoke trail or plume from a tall stack located on flat terrain has been found to exhibit a characteristic shape that is dependent on the stability of the atmosphere.
- There are six classical plumes as shown in *Figure 14* and these are strong laps condition (looping), weak laps condition (coning), inversion condition (fanning), inversion below, lapse aloft (lofting), lapse below, inversion aloft (fumigation), and weak lapse below, inversion aloft (trapping).



Plume:

- The dispersion of **emitted gases** from the source of their production is known as **plume** and the source is known as **stack**.



Figure 13: Example Inversion from power plants

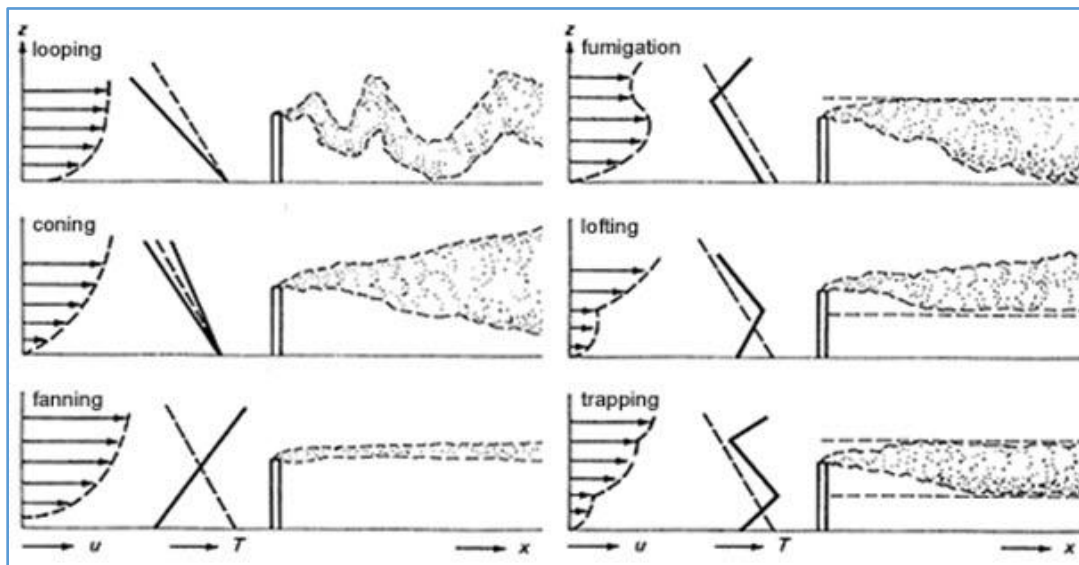


Figure 14: Air pollution plumes: looping, fumigation, coning, lofting, fanning, and trapping

Example 3: Given the following temperature profiles, determine whether the atmosphere is unstable, neutral, or stable. Show all work and explain choices.

a.	Z,m	T,°C	b.	Z,m	T,°C	c.	Z,m	T,°C
	2	- 3.05		10	6.00		18	14.03
	318	- 6.21		202	3.09		286	16.71

Example 3: Solutions

(a)

$$\frac{\Delta T}{\Delta Z} = \frac{T_2 - T_1}{Z_2 - Z_1} \times 100 \text{ } ^\circ\text{C} / 100\text{m}$$

$$= \frac{-6.21 - (-3.05)}{318 - 2} \times 100 = -1^\circ C / 100m = \Gamma, \text{ Neutral}$$

(b)

$$\frac{\Delta T}{\Delta Z} = \frac{3.09 - 6.00}{202 - 10} \times 100 = -1.5^\circ C / 100m < \Gamma, \text{ Unstable}$$

(c)

$$\frac{\Delta T}{\Delta Z} = \frac{16.71 - 14.03}{286 - 18} \times 100 = 1.0^\circ C / 100m > \Gamma, \text{ Stable}$$

10.4 Terrain Effects

Heat Islands

A heat island results from a mass of material, either natural or anthropogenic, that absorbs and reradiates heat at a greater rate than the surrounding area. This causes moderate to strong vertical convection currents above the heat island. The effect is superimposed on the prevailing meteorological conditions. It is nullified by strong wind. Because of the heat island effect, atmospheric stability will be less over a city than it is over the surrounding countryside. Depending on the location of the pollutant sources, this can be either good news or bad news.

The good news is: for ground level sources such as automobiles, the bowl of unstable air that forms will allow greater air volume for dilution of the pollutants.

The bad news is: Under stable conditions, plumes from the stacks would be carried out over the countryside without increasing ground level pollutant concentrations.

Unfortunately, the instability caused by the heat island mixes these plumes to the ground level.

Land/sea breezes

Under a staging anticyclone, a strong local circulation pattern may develop across the shoreline of large water bodies. During the night land cools more rapidly than the water. The relatively cooler air over the land flows toward the water (*a land breeze*, Figure 15).

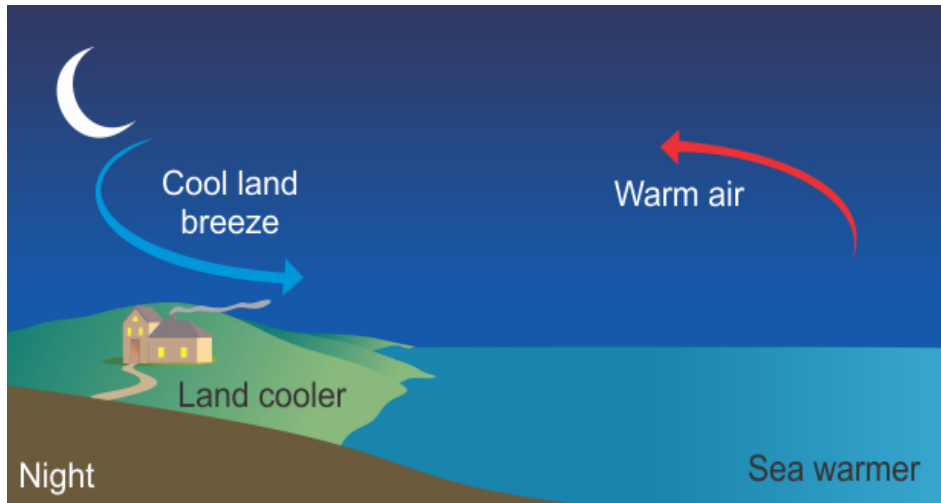


Figure 15: Land breeze during night

During the morning, the land heats faster than water. The air over the land becomes relatively warm and begins to rise. The rising air is replaced by air from over the water body (*a sea or lake breeze*, Figure 16). The effect of the lake breeze on stability is to impose a surface-based inversion on the temperature profile. As the air moves from the water over the warm ground, it is heated from below. Thus, for stack plumes generating near the shoreline, the stable lapse rate causes a fanning plume close to the stack (Figure 17).

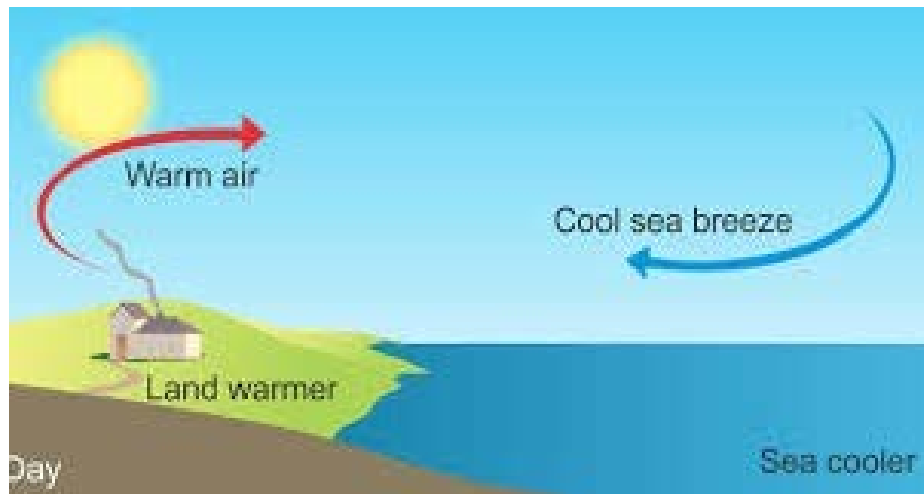


Figure 16: Lake breeze during the day

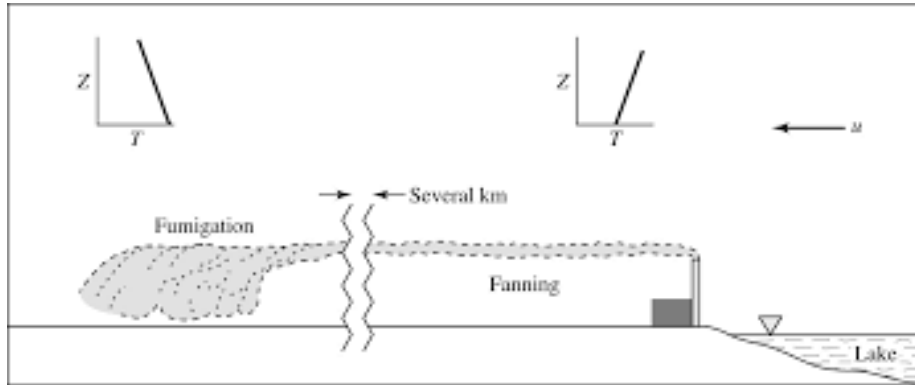


Figure 17: Effect of lake breeze on plume dispersion

11. Atmospheric Dispersion

The accidental or intentional release of chemical, biological, or nuclear agents, as well as ash associated with volcanic eruptions, can have significant health, safety, national security, economic, and ecological implications. Several govt organizations have an Atmospheric Dispersion Research Program that provides critical modeling and observation data to understand how, where, and when chemicals and materials are transported through the atmosphere. Having this understanding is essential for emergency managers and the aviation industry to respond appropriately and minimize or prevent disaster. A schematic of atmospheric dispersion of air pollutants is shown in *Figure 18*.

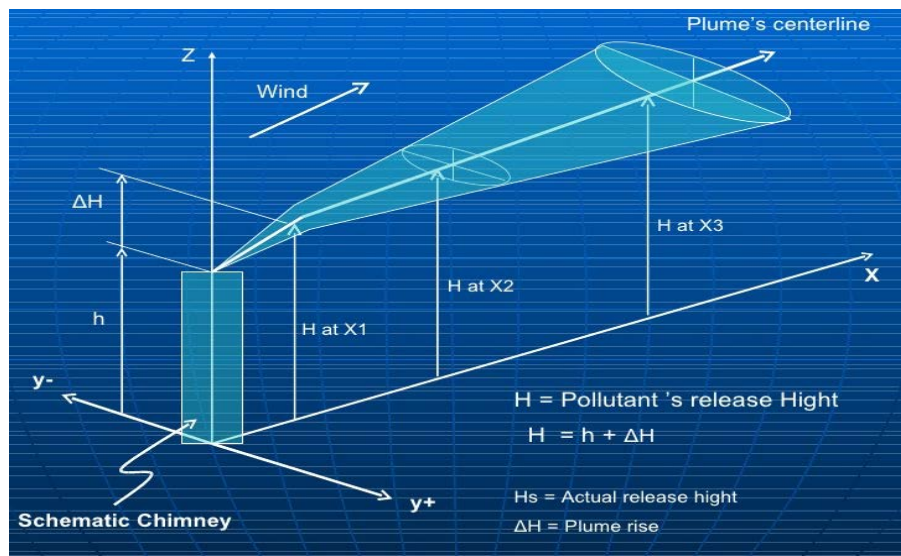


Figure 18: Atmospheric dispersion

11.1 Factors Affecting Dispersion

The factors affecting the transport, dilution, and dispersion of air pollutants can generally be categorized in terms of:

- the emission point/source characteristics,
- the nature of the pollutant material,
- Meteorological conditions, and
- The effects of terrain and anthropogenic structures.

Source characteristics:

Most of the effluents are discharged vertically into the open air through a stack or duct. As the contaminated gas stream leaves the discharge point, the plume tends to expand and mix with the ambient air. Horizontal air movement will tend to bend the discharged plume toward the downwind direction. At some point between 300-3,000 m downwind, the effluent plume will level off. While the effluent plume is rising, bending, and beginning to move in a horizontal direction, the gaseous effluents are being diluted by the ambient air surrounding the plume. As the contaminated gases are diluted by larger and larger volumes of ambient air, they are eventually dispersed toward the ground. The plume rise, together with the physical stack height is called *the effective stack height*.

Downwind distance:

The greater the distance between the point of discharge and a ground level receptor downwind, the greater will be the volume of air available for diluting the contaminated discharge it reaches the receptor.

Wind speed and direction:

Wind speed affects the plume rise and rate of mixing or dilution of the contaminated gases as they leave the discharge point. An increase in wind speed will decrease the plume rise by bending the plume over more rapidly. The decrease in plume rise tends to increase the pollutant's ground level concentration. On the other hand, an increase in wind speed will increase the rate of dilution of the effluent plume, tending to lower the downwind concentrations. The wind direction determines the direction in which the contaminated gas stream will move across local terrain.

Stability:

The turbulence of the atmosphere follows no other factor in power of dilution. The more unstable the atmosphere, the greater the diluting power. Inversions that are not ground based, but begin at some height above the stack exit, act as a lid to restrict vertical dilution.

11.2 Dispersion Modeling

A dispersion model is a mathematical description of the meteorological transport and dispersion process that is quantified in terms of source and meteorological parameters during a particular time. The resultant numerical calculations yield estimates of concentrations of particular pollutant for specific locations and times.

Steps in modeling

- **Development** – formulation of equations using different parameters.
- **Solution** – Solve the equations either by analytical, statistical, and/or numerical techniques.
- **Calibration** – verify the model results with actual filed data.

Models are usually classified as either short-term or climatological (long-term) models. Short-term models are used under the following circumstances:

- To estimate ambient concentrations where it is impractical to sample, such as over rivers or lakes, or a great distance above the ground.
- To estimate the required emergency source reductions associated with period of air stagnations under air pollution episode alert condition, and
- To estimate the most probable locations of high, short-term, ground level concentrations as part of a site selection evaluation for the location of air monitoring equipment.

Climatological models are used under the following circumstances:

- To estimate mean concentrations over a long period of time or to estimate means concentrations that exist at particular times of the day for each season over a long period of time.
- As an aid for developing emission standards

Basic point source Gaussian dispersion model:

- The model equation assumes that atmospheric stability is uniform throughout the layer which the contaminated gas stream is discharged.
- Turbulence diffusion is a random activity and hence dilution of the contaminated gas stream in both the horizontal and vertical direction can be described by the Gaussian or normal equation.
- The contaminated gas stream is released into the atmosphere at a distance above ground level that is equal to the effective stack height (*physical stack height plus the plume rise*).

- The degree of dilution of the effluent plume is inversely proportional to the wind speed (u).
- Pollutant material that reaches ground level is totally reflected back into the atmosphere like a beam of light striking a mirror at an angle. Mathematically, this ground reflection is accounted for by assuming a virtual or imaginary source located at a distance of $-H$ with respect to ground level and emitting an imaginary plume with the same source strength as the real source being modeled.

The model:

The model equation selected is in the form presented by *D.B. Turner* which gives the ground level concentration (C) of pollutant at a point ($x, y, 0$) downwind from a stack with an effective height (H). The equation is as follows:

$$C(x, y, 0, H) = \frac{E}{\pi s_y s_z u} e^{-\frac{1}{2}\left(\frac{y}{s_y}\right)^2} e^{-\frac{1}{2}\left(\frac{H}{s_z}\right)^2} \dots\dots\dots (18)$$

where, $C(x,y,0,H)$ = downwind concentration at ground level, g/m^3 .

E = emission rate of pollutant, g/s

s_y, s_z or σ_y, σ_z = plume standard deviations, m in horizontal and vertical direction (depend on turbulent structure or stability of the atmosphere)

u = wind speed, m/s

$x, y, z,$ and H = distances, m ; and e = exponent = 2.7182

The value of effective stack height is the sum of the physical stack height (h) and the plume rise ΔH , i.e. $H = h + \Delta H$

ΔH may be computed from Holland’s formula as follows:

$$\Delta H = \frac{v_s d}{u} \left[1.5 + \left(2.68 \times 10^{-2} (P) \left(\frac{T_s - T_a}{T_s} \right) d \right) \right] \dots\dots\dots (19)$$

where, v_s = stack velocity, m/s . d = stack diameter, m ; u = wind speed, m/s ; P = pressure, kPa

T_s = stack temperature, K ; T_a = air temperature, K

For computer solutions of the dispersion model, it is convenient to have an algorithm to express the stability class lines in Figure 18 and Figure 19.

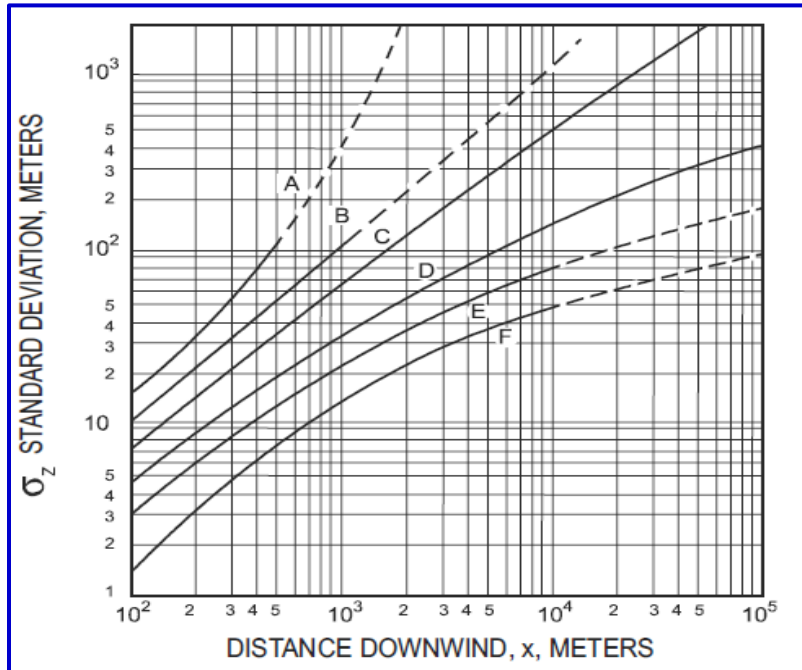


Figure 19: Vertical standard deviation of a plume

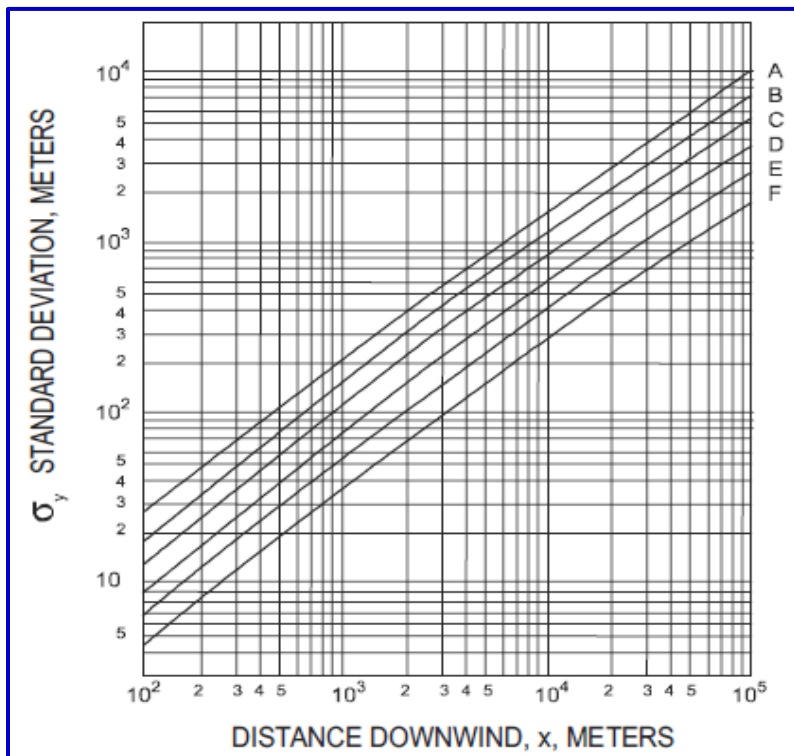


Figure 20: Horizontal standard deviation of a plume

Inversion aloft: When an inversion is present, the basic diffusion equation must be modified to take into account the fact that the plume cannot disperse vertically once it reaches the inversion layer.

The plume will begin to mix downward when it reaches the base of the inversion layer (Figure 21). The following empirically equation is used to determine the vertical standard deviation of the plume at a distance x_L :

$$\sigma_z \text{ or } s_z = 0.47(L - H) \dots \dots \dots (20)$$

where $L =$ height to bottom of the inversion layer, m

$H =$ effective stack height, m

When the plume reaches twice the distance to initial contact with the inversion base, the plume is said to be completely mixed throughout the layer below the inversion. Beyond a distance equal to $2x_L$ the centerline concentration of pollutants may be estimated using the following equation (called **inversion** dispersion equation):

$$C = \frac{E}{(2\pi)^{1/2} s_y(u)(L)} \dots \dots \dots (21)$$

where, s_y is determined by the stability of the layer below the inversion and the distance to the receptor.

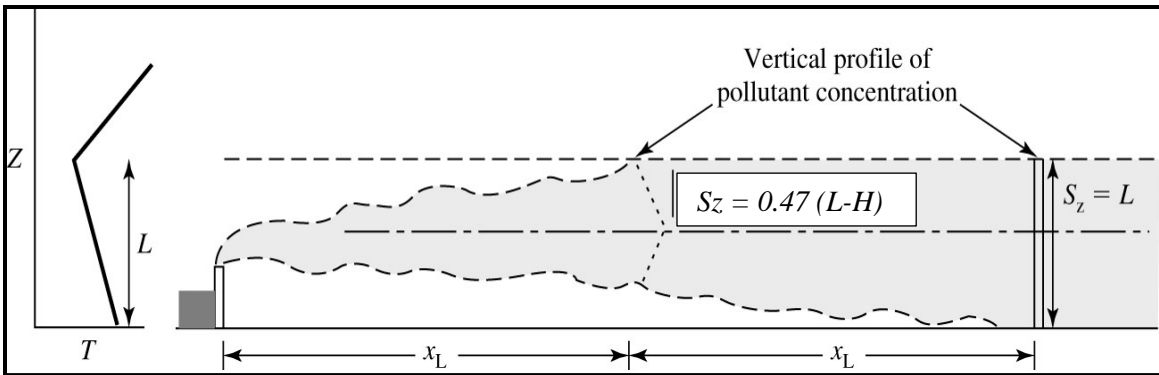


Figure 21: Effect of elevated inversion on dispersion

Table 4: Atmospheric stability under various conditions

Atmospheric Stability Under Various Conditions					
Surface Wind Speed ^a (m/s)	Day Solar Insolation			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

Notes:

- 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 the 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.

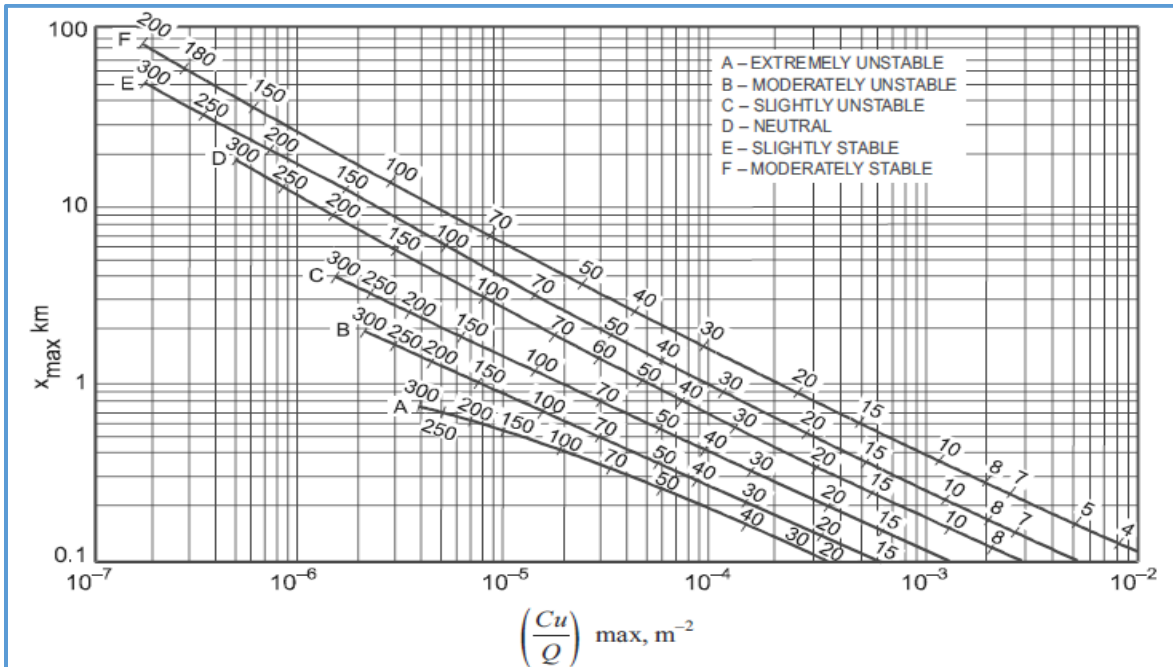


Figure 22: Relationship of effective stack height with Cu/Q and max distance

Table 5: Values of constants for various stability class

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

Stability	Constants			
	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, R.J.P., 1976.

$$\left(\frac{Cu}{Q}\right)_{max} = e^{[a+b \ln H+c(\ln H)^2+d(\ln H)^3]} \dots\dots\dots (22)$$

Example 4: Calculate the downwind concentration at 30 km ($y = 0$) in g/m^3 resulting from an emission of 1,976 g/s of SO_2 into a 2.5 m/s wind at 1:00 am on a clear winter night. Assume an effective stack height of 85 m and an inversion layer at 185 m. Identify the stability and show all work.

Example 4: Solutions

Given: Stack parameters, emission rate, $E = 1976$ g/s of SO_2 , wind speed $u = 2.5$ m/s, 1:00 AM, on clear winter night, effective stack height $H = 85$ m, inversion layer at $L = 185$ m

(a) Determine stability class

Based on clear sky at night and wind speed = 2.5 m/s, from Table 4 stability category is **F** (clear night)

(b) Check x_L (Using Eq. 20)

$$S_z = 0.47(L-H) = 0.47(185 - 85) = 47 \text{ m}$$

With stability class F and $S_z = 47$, find x_L @ 10 km (from Figure 18) $2x_L = 20$ km.

Because 30 km > 20 km use Equation 21

$$C = \frac{E}{(2\pi)^{1/2} s_y(u)(L)}$$

© Calculate σ_y using Figure 19

$$\sigma_y \text{ or } S_y = 600$$

(d) Calculate downwind concentration (Using Eq. 21)

$$C = \frac{E}{(2\pi)^{1/2} \sigma_y(u)(L)} = \frac{1976}{(2\pi)^{1/2}(600)(2.5)(185)} = 2.8 \times 10^{-3} \text{ g/m}^3 \text{ Ans.}$$

Alternate Solutions:

Given: Stack parameters, emission rate, $Q = 1976 \text{ g/s}$ of SO_2 , wind speed $u = 2.5 \text{ m/s}$, 1:00 AM, on clear winter night, effective stack height $H = 85 \text{ m}$, inversion layer at $L = 185 \text{ m}$

(a) Determine stability class

Based on clear sky at night and wind speed, $u = 2.5 \text{ m/s}$, from Table 4, stability category is **F**

(b) For stability class **F**, $a = -1.0488$, $b = -3.2252$, $c = 0.4977$, and $d = -0.0765$ (Table 5). Using the equation 22,

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

$$\frac{C_u}{Q} = e^{[a+b \ln H + c(\ln H)^2 + d(\ln H)^3]} = e^{[-1.0488 - 3.2252 \ln 85 + 0.4977 (\ln 85)^2 - 0.0765 (\ln 85)^3]}$$

$$= e^{-1.0488 - 14.3284 + 9.8232 - 6.7079} = e^{-12.2619} = 4.729 \times 10^{-6} \text{ m}^{-2}$$

$$C_{\max} = \left(\frac{C_u}{Q} \right) \left(\frac{Q}{u} \right) = 4.729 \times 10^{-6} \text{ m}^{-2} \left(\frac{1976 \text{ g/s}}{2.5 \text{ m/s}} \right) = 3.74 \times 10^{-3} \text{ g/m}^3 \text{ ANS.}$$

Example 5: Given the meteorological and power plant data shown below, determine the maximum downward concentration of SO_2 and the distance from the stack that it occurs.

Meteorological conditions:

wind speed at 10 m, $u = 4 \text{ m/s}$

sunny summer after noon

Power Plant conditions:

SO₂ emission rate, Q (or E) = 151 g/s

Effective stack height, $H = 150$ m

Example 5: Solutions

(a) Determine stability class

From Table 4, at wind speed of 4 m/s under strong solar radiation condition, the stability class is B.

(b) For stability class B, From Figure 21, for $H = 150$ m, $X_{max} = 1$ km and $(C_u/Q)_{max} = 7.5 \times 10^{-6} \text{ m}^{-2}$

$$C_{max} = \left(\frac{Cu}{Q}\right)\left(\frac{Q}{u}\right) = 7.5 \times 10^{-6} \text{ m}^{-2} \left(\frac{151 \text{ g/s}}{4 \text{ m/s}}\right) = 2.8 \times 10^{-4} \text{ g/m}^3 \quad \text{ANS.}$$

that will occur at a distance of 1 km. **ANS.**

For stability class B, $a = -1.8060$, $b = -2.1912$, $c = 0.0389$, and $d = 0$ (Table 5).

Using equation 22,

$$\left(\frac{C_u}{Q}\right)_{max} = e^{[a+b \ln H + c(\ln H)^2 + d(\ln H)^3]} = e^{[-1.8060 - 2.1912(\ln 150) + 0.0389(\ln 150)^2 + 0]}$$

$$= e^{-1.8060 - 10.9793 + 0.9766} = 7.44 \times 10^{-6} \text{ m}^{-2} \quad \text{which is close to what we got from graph}$$

12. Indoor Air Quality Model

A simple mass balance model to explore the behavior of the indoor air quality as a function of infiltration of outdoor, indoor sources and sinks, and leakage to outdoor air can be constructed considering a room or a confined space as simple box as follows (Figure 23):

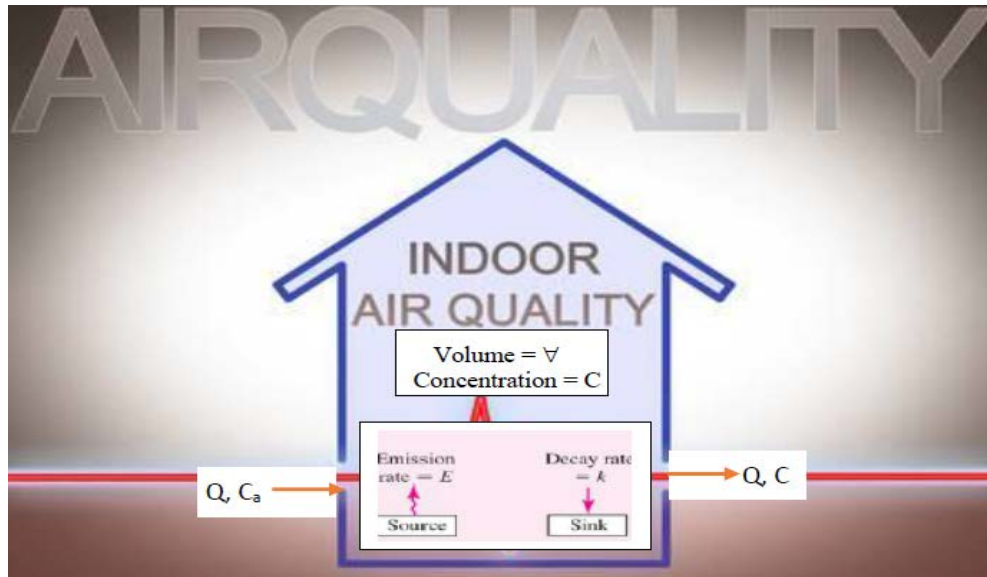
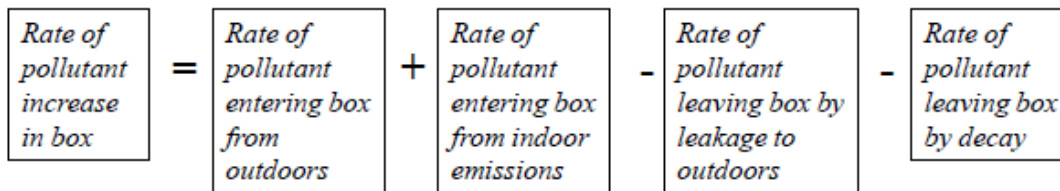


Figure 23: Indoor air quality model diagram



$$\text{Or } V \frac{dC}{dt} = QC_a + E - QC - kC V \dots \dots \dots (23)$$

where, V = volume of box, m^3

C = concentration of pollutant, g/m^3

Q = rate of infiltration of air into and out of box, m^3/s

C_a = concentration of pollutant in outdoor air, g/m^3

E = emission rate of pollutant into box from indoor source, g/s

k = pollutant reaction rate coefficient, s^{-1}

Reaction rate coefficients for a selected list of pollutants are presented in literature. The general solution for **Eq.(23)** is

$$C_t = \frac{\frac{E}{V} + C_a \frac{Q}{V}}{\frac{Q}{V} + k} \left[1 - e^{-\left(\frac{Q}{V} + k\right)t} \right] + C_o e^{-\left(\frac{Q}{V} + k\right)t} \dots \dots \dots (24)$$

The steady-state solution for Eq.(23) may be found by setting $dC/dt = 0$ and solving for C :

$$C = \frac{QC_a + E}{Q + kV} \dots\dots\dots (25)$$

When the pollutant is conservative and does not decay with time, or have significant reactivity, $k = 0$. In the special case when the pollutant is conservative and the ambient air concentration is negligible and the initial indoor concentration is zero, the Eq.(23) reduces to:

$$C_t = \frac{E}{Q} \left[1 - e^{-\left(\frac{Q}{V}\right)t} \right] \dots\dots\dots (26)$$

13. Air Pollution Control of Stationary Sources

There are two types of air pollutant and these are:

1. Gaseous Pollutants
2. Particulate Pollutants

In addition to the above two air pollutants, Flue Gas Desulfurization and Control Technologies for Nitrogen Oxides are also employed to control air pollution from stationary sources.

13.1 Gaseous Pollutants

The control devices/technologies used to control gaseous air pollutants from stationary sources are based on the **principle** of:

1. Absorption,
2. Adsorption, and
3. Combustion

Absorption:

Transfer the pollutant from a gas phase to a liquid phase. This is a mass transfer process in which gas dissolves in liquid. Mass transfer is a diffusion process wherein the pollutant gas moves from points of higher concentration to points of lower concentration. The removal of the pollutant gas takes place in three steps:

1. Diffusion of pollutant gas to the surface of the liquid,
2. Transfer across the gas/liquid interface (dissolution), and
3. Diffusion of the dissolved gas away from the interface into the liquid.

Structures such as *spray chambers*, and *towers or columns* are two classes of devices employed to absorb pollutant gases. An example of absorption column is illustrated below (*Figure 23*).

Absorption Column: Gas and liquid are passed through the tube in countercurrent flow. Before the gas leaves at the top of the column, entrained scrubbing liquid drops are retained by adequate droplet separators. The column is usually placed on a container, which contains the scrubbing liquor. All wastewater is let out through an overflow or a pump.

The vertically standing tube is equipped inside with fittings enabling intensive contact between washings and exhaust. The choice of fittings depends on the respective cleaning task and the composition of the exhaust gas.

Gas and washing travel through a counter-flow scrubbing column. In doing so, the exhaust gas to be cleaned enters sideways at the lower end of the column and is led upwards to the upper end of the column. The washing liquor is distributed over the entire tube cross-section and trickles down along the column internals, where it is collected in a container.

In the case of a physical absorption, the scrubbing liquor lead through the column tube in one single pass. In the case of a chemical absorption, the scrubbing liquid is circulated through a centrifugal pump. Occurring wastewater is separated in the container via an overflow or via level-controlled pump (*Figure 25*). The counter-flow arrangement results in a maximum exploitation of the concentration difference between exhaust gas and scrubbing fluid which is an important motive factor for absorption. The maximum cleaning effect is achieved as a factor of the column height.



Figure 24: Absorption Column

The naming of the column type depends on the kind of column internals. A distinction is made between:

- Packed-bed columns
- Packed columns
- Plate columns
- Spray columns

The ranges of application of the columns are 100 – 150,000 m³/h exhaust gas and the exhaust gases are cleaned through chemical or physical absorption.

Adsorption:

A mass transfer process in which the gas is bonded to a solid. It is an interface phenomenon. The gas (the *adsorbate*) penetrates into the pores of the solid (the *adsorbent*) but into the lattice itself. The bond may be physical or chemical. Electrostatic forces hold the pollutant gas when physical bonding is significant. Chemical bonding is by reaction with the surface. *Activated charcoal, molecular sieves, silica gel, and the activated alumina* are the most common adsorbents. An example of adsorption system is shown in *Figure 26*.



Figure 25: Adsorption systems

Adsorption Isotherm

The relation between the amount of pollutant adsorbed and the equilibrium pressure at constant temperature is called adsorption Isotherm. The equation that describes this relation for gases is the one derived by Langmuir (1918):

$$W = \frac{aC_g}{1 + bC_g} \dots \dots \dots (27)$$

where, W = amount of gas per unit mass of adsorbent (kg/kg)

a, b = constant determined by experiments

C_g = equilibrium conc. of gaseous pollutants, (g/m³)

In the analysis of experimental data, the equation is rearranged as follows:

$$\frac{C_g}{W} = \frac{1}{a} + \frac{b}{a}C_g \rightarrow \text{equivalent to } y = c + mx$$

A plot of C_g/W versus C_g is a straight line as shown above and yields a slope (b/a) and a y-intercept ($1/a$).

Combustion:

Combustion is a possible alternative when the contaminant in the gas stream is oxidizable to an inert gas. Typically, CO and hydrocarbons fall into this category. Both direct flame combustion by afterburners and the catalytic combustion have been used in commercial application. An example of direct flame combustion system is shown in *Figure 27*.

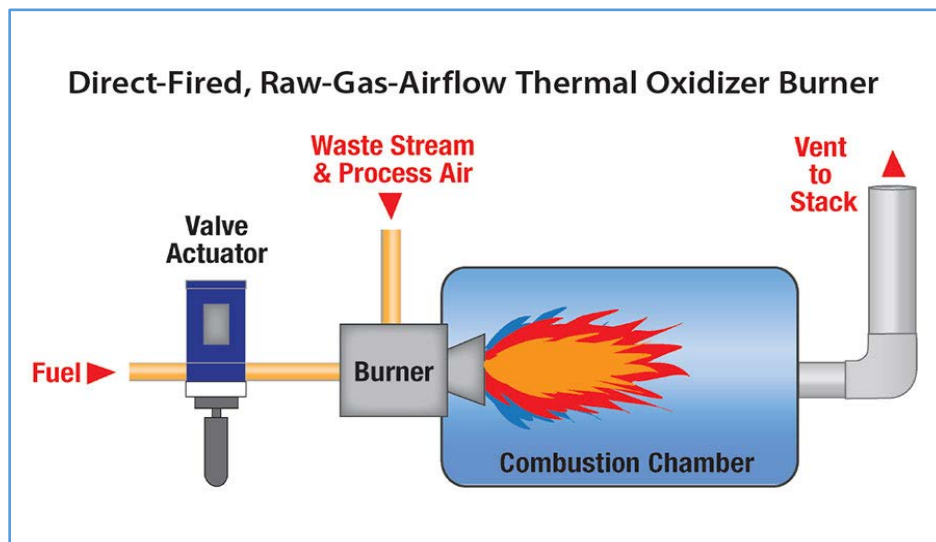


Figure 26: Direct flame incineration

13.2 Particulate Pollutants

For controlling particulate pollutants, usually the following control devices are used:

1. Cyclone
2. Filter
3. Liquid scrubbing
4. Electrostatic precipitator (ESP)

Cyclone

It is used to collect particle sizes greater than 10- μm in diameter. This is an inertial collector with no moving parts. The particulate-laden gas is accelerated through a spiral motion, which imparts a centrifugal force to the particles. The particles are hurled out of the spinning gas and impact the cylinder wall of the cyclone. They then slide to the bottom of the cone. Here they are removed through an airtight valving system (*Figure 28*).

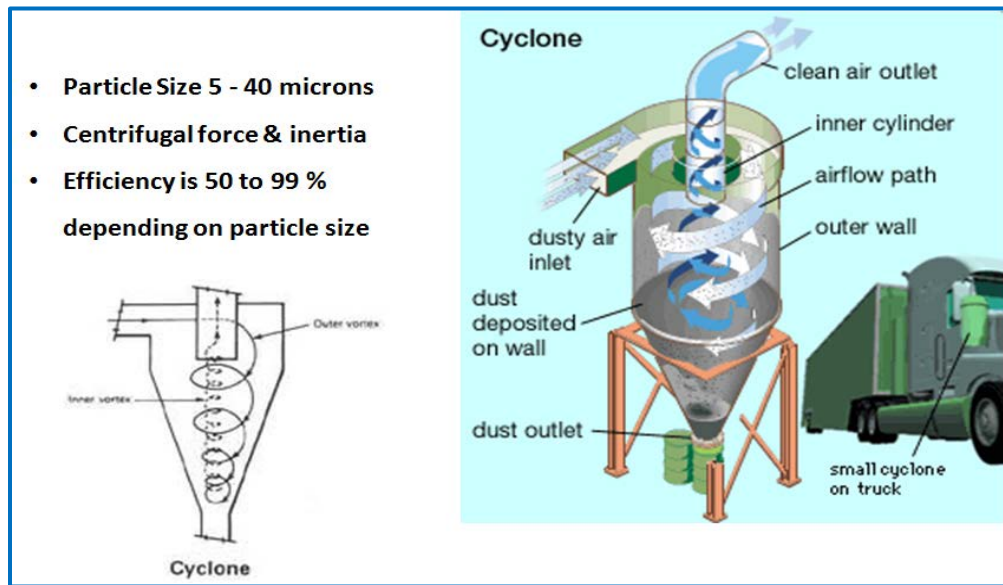


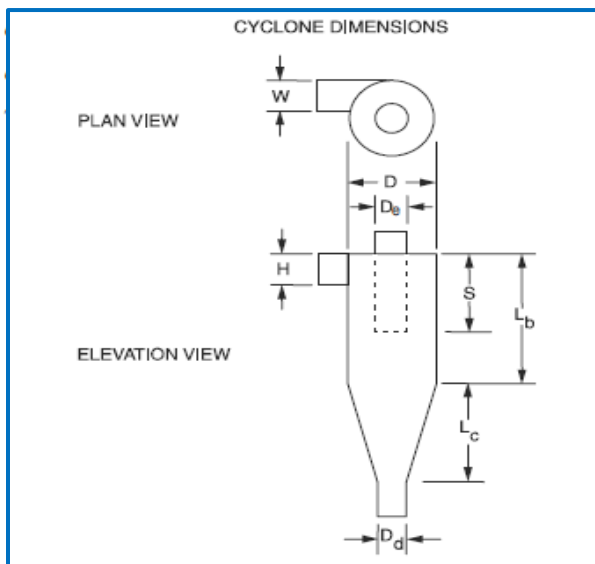
Figure 27: Cyclone

The following Figures, Tables, and the equations can be used to estimate the efficiency and design of a standard cyclone.

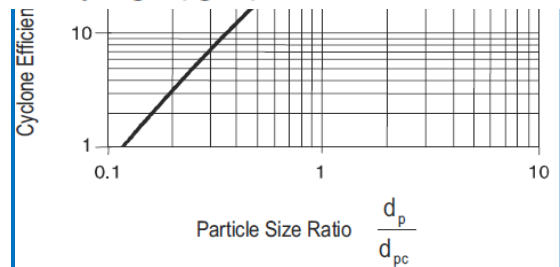
Cyclone Collection (Particle Removal) Efficiency

$$\eta = \frac{1}{1 + (d_{pc}/d_p)^2}, \text{ where}$$

$$d_{pc} = \left[\frac{9\mu W}{2\pi N_e V_i (\rho_p - \rho_g)} \right]^{0.5}, \text{ where}$$



d_{pc} = diameter of particle that is collected with 50% efficiency (m),
 μ = dynamic viscosity of gas (kg/m*s),
 W = inlet width of cyclone (m),
 N_e = number of effective turns gas makes in cyclone,
 V_i = inlet velocity into cyclone (m/s),
 ρ_p = density of particle (kg/m³), and
 ρ_g = density of gas (kg/m³).



Cyclone Effective Number of Turns Approximation

$$N_e = \frac{1}{H} \left[L_b + \frac{L_c}{2} \right], \text{ where}$$

N_e = number of effective turns gas makes in cyclone,

H = inlet height of cyclone (m),

L_b = length of body cyclone (m), and

L_c = length of cone of cyclone (m).

Cyclone Ratio of Dimensions to Body Diameter

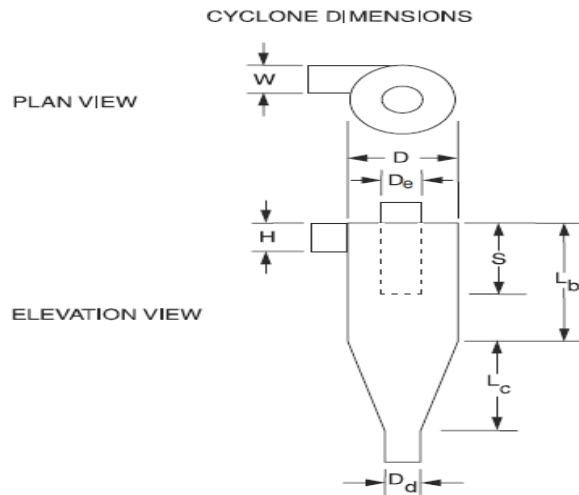
Dimension	High Efficiency	Conventional	High Throughput
Inlet height, H	0.44	0.50	0.80
Inlet width, W	0.21	0.25	0.35
Body length, L_b	1.40	1.75	1.70
Cone length, L_c	2.50	2.00	2.00
Vortex finder length, S	0.50	0.60	0.85
Gas exit diameter, D_e	0.40	0.50	0.75
Dust outlet diameter, D_d	0.40	0.40	0.40

Example 6: Design a "standard" cyclone for a removal efficiency of 45% for the removal of 2.50- μm -diameter particle having a density of 1,250 kg/m^3 for a cyclone barrel diameter of 1.0 m. The gas flow rate is 2.80 m^3/s and the gas temperature are 25°C. Show the dimensions in drawing(s).

Example 6: Solutions

Particle diameter, $d_p =$	2.5	μm					
Particle density, $\rho_p =$	1250	kg/m^3					
Gas flow rate, $Q_g =$	2.8	m^3/s					
Gas temperature, $T_g =$	25	$^{\circ}\text{C} =$	298	K			
Efficiency, $\eta =$	45%						
Viscosity of air, $\mu =$	3.308E-05	Pa.s	$\mu = [17.11 + 0.0536 (T) + (P/8280)] \mu\text{Pa.s}, T = K \text{ and } P = \text{kPa}$				
	3.372E-06	$\text{kg}/\text{m.s}$					
Air density, $\rho_g =$	1.185	kg/m^3 at 25°C					

Using the relationships:	High Throughput
Length of cylinder, $L_b =$	1.7 D
Length of cone, $L_c =$	2 D
Diameter of exit, $D_e =$	0.75 D
Height of entrance, $H =$	0.8 D
Width of entrance, $W =$	0.35 D
Diameter of dust exit, $D_d =$	0.4 D
Vortex finder length, $S =$	0.85 D



Inlet velocity, $V_i = Q_g/(HW) = 2.8/(0.8D \times 0.35D) =$	<input type="text" value="10.00"/>	$/D^2$		
From efficiency equation,				
Cut diameter, $d_{pc} = d_p \sqrt{\left(\frac{1}{\eta} - 1\right)}$				
$= 2.5 \text{ SQRT}(1/0.45 - 1) =$	<input type="text" value="2.764"/>	$\mu\text{m} =$	<input type="text" value="2.7639E-06"/>	m
Number of effective turns, $N_e = \frac{1}{H} \left[L_b + \frac{L_c}{2} \right]$				
$= (1/0.8D) \times [1.7D + 2D/2] =$	<input type="text" value="3.38"/>			

$d_{pc} = \left[\frac{9\mu W}{2\pi N_e V_i (\rho_p - \rho_g)} \right]$			
$0.00000276 = [9 \times 0.00000337 \times 0.35D / (2 \times 3.14159 \times 3.375 \times 10 / D^2 (1250 - 1.185))]^{(1/2)}$			
2.76385E-06	=	6.33E-06	$D^{(3/2)}$
$\therefore D = (0.00000276 / 0.00000633)^{(2/3)} = 0.58 \text{ m ANS.}$			
Length of cylinder, $L_b =$	$1.7D =$	0.978	m
Length of cone, $L_c =$	$2D =$	1.151	m
Diameter of exit, $D_e =$	$0.75D =$	0.431	m
Height of entrance, $H =$	$0.8D =$	0.460	m
Width of entrance, $W =$	$0.35D =$	0.201	m
Diameter of dust exit, $D_d =$	$0.4D =$	0.230	m
Vortex finder length, $S =$	$0.85D =$	0.489	m

Filters

When high efficiency control of small particles smaller than 5-µm is desired, a filter may be selected as the control method. Two types are in use:

- The deep bed filter, and
- The baghouse (*Figure 29*)

The *deep bed* filter resembles a furnace filter. A packing of fibers is used to intercept particles in the gas stream.

For relatively clean gases and low volumes, such as air conditioning systems, these are quite effective. For dirty industrial gas with high volumes, the bag house is preferable. The fundamental mechanisms of collection by filters include screening or sieving because the particles are larger than the openings between the fibers, interception by the fibers themselves, and electrostatic attraction because of the difference in static charge on the particle and fiber.

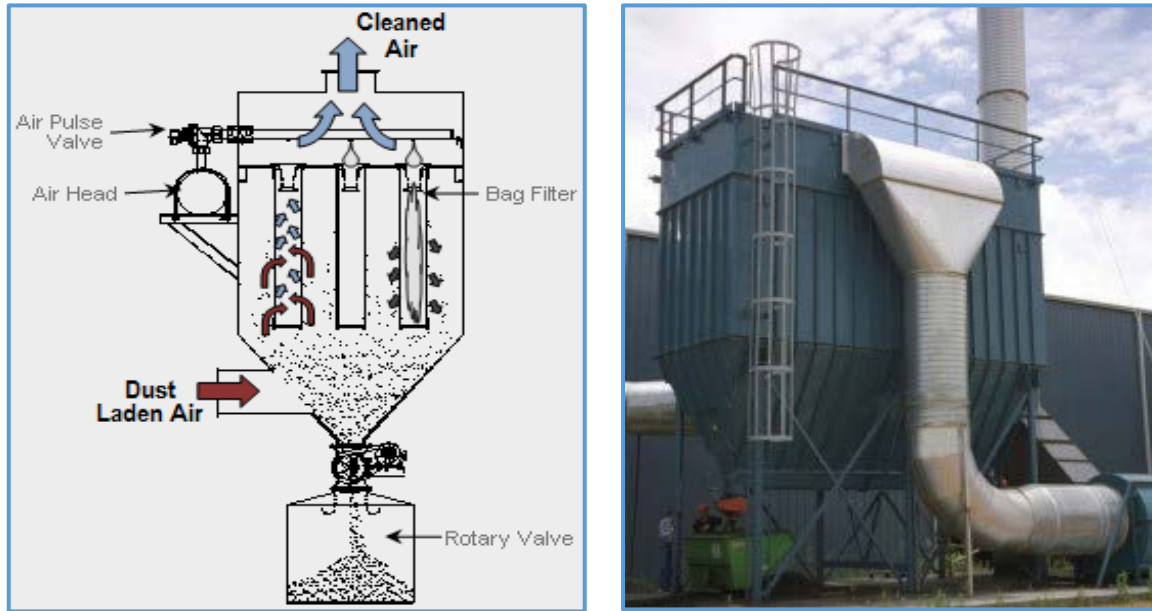


Figure 28: Fabric filter bag house

The bags are made of either natural or synthetic fiber. Synthetic fibers are widely used as filtration fabrics because of their low cost, better temperature- and chemical-resistance characteristics, and small fiber diameter. Bag life varies between 1 and 5 years, 2 years is considered normal. Bag diameters range from 0.1 to 0.35 m, and lengths vary between 2 to 10 m. The bags are suspended from the toe and fastened by a collar at the open end. They are arranged in groups in separate compartment.

Example 7: A consultant has proposed that a pulse-jet baghouse with bags that are 15 cm in diameter and 5 m in length be used instead of the mechanical shaker bag system. Estimate the net number of bags required for a gas flow rate of 20 m³/s, if the manufacturer’s recommended air-to-cloth ratio of aggregate plants is 0.050 m/s and 1 in 8 bags are taken offline for cleaning.

Example 7: Solutions

Data Given				
Gas flow rate, $Q_g =$	20	m ³ /s		
Bag diameter, $d =$	15	cm =	0.15	m
Bag length, $L =$	5	m		
Bag taken off-line =	1	8		
Air-to-cloth ratio, $v =$	0.050	m/s = m ³ /m ² .s		

Cloth required for one compartment, $A =$	$\frac{Q_g}{v}$	=	$\frac{20}{0.050}$	=	400	m ²
The net number of bags required is =	$\frac{A}{\pi \times d \times L}$	=	$\frac{400}{3.14159 \times 0.15 \times 5}$	=	169.77	
					≈	170
With off-line of 1/8th bags, number of bas required		=	$170 + 170/8$			
		≈	192		ANS.	

Liquid Scrubber

Liquid scrubbing might work when the particulate matter to be collected is wet, corrosive, or very hot and the fabric filter may not work. Typical scrubbing applications include control of emission of talc dust, phosphoric acid mist, foundry cupola dust, open hearth steel furnace fumes. Simple spray chambers are used for relatively coarse particle sizes. For high efficiency removal of fine particles, the combination of a venturi scrubber followed by a cyclone would be selected. For high efficiency removal of fine particles, the combination of a venturi scrubber followed by a cyclone would be selected. Vertically standing tube with Venturi throat and displace (Venturi cone - *Figure 30*) and spray nozzles arranged concentrically in the tube, above the Venturi throat. The exhaust gas flows from above or sideways into the tube. Usually in combination with a laterally centrifugal separator. Venturi scrubbers are high performance separators for fine dusts and aerosols.

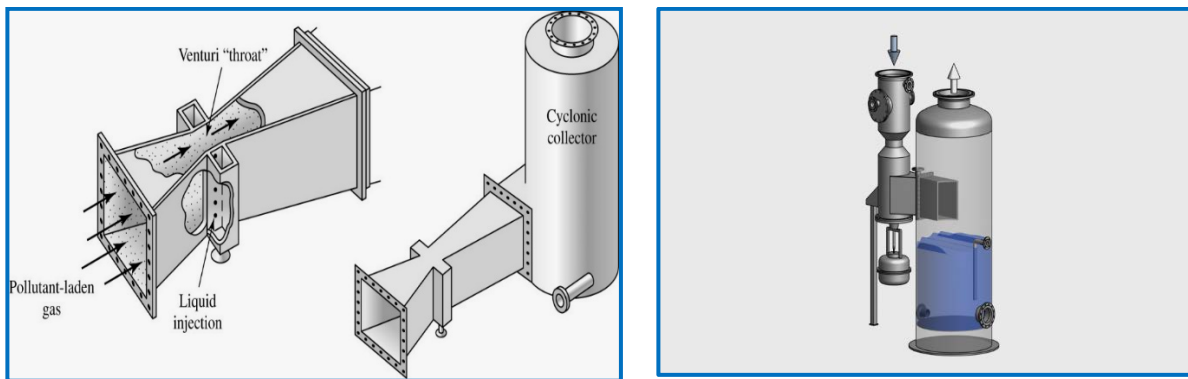


Figure 29: Venturi scrubber

A differential velocity between the droplet of the collecting liquid and the particulate pollutant allows the particle to impinge onto the droplet. Since the droplet-particle combination is still suspended in the gas stream, an inertial collection device is placed downstream to remove it. Because the droplet enhances the size of the particle, the collection efficiency of the inertial device is higher than it would be for the original particle without the liquid drop.

Example 8: Calculate the overall mass efficiency (η) of the venturi scrubber with throat area of 1.0 m², gas flow rate of 94.4 m³/s, gas temperature of 150°C, liquid flow rate of 0.13 m³/s and

droplet diameter of 100- μm for the following particle size distribution. Assume, coefficient $k = 200$ and particles are fly-ash with a density of 700 kg/m^3 and a minimum size of 10- μm diameter.

Average diameter (μm)	2.5	7.5	15	25	35	30
% of total	25	20	15	15	10	15

Example 8: Solutions

Particle diameter, $d_p =$	1.00	$\mu\text{m} =$	0.000001	m
Particle density, $\rho_p =$	700	kg/m^3		
Throat area, $A_t =$	1.00	m^2		
Gas flow rate, $Q_g =$	94.40	m^3/s		
Gas temperature, $T_g =$	150	$^\circ\text{C} =$	423	K
Efficiency, $\eta =$?			
Liquid flow rate, $Q_L =$	0.13	m^3/s		
Coefficient, $\kappa =$	200			
Water droplet diameter, $d_d =$	100	$\mu\text{m} =$	0.0001	m
Viscosity of gas, $\mu =$	2.520E-05	Pa.s (Table A-4 or literature		

Cunningham correction factor, $C = 1 + \frac{6.21 \times 10^{-4}(T)}{d_p} = 1 + \frac{6.21 \times 10^{-4}(423)}{1.00} = 1.105$

Therefore for all particles $> 2.5\mu\text{m}$ we can see that the term containing d_p will be small and can use the approximation $C = 1$.

Gas velocity at throat, $v_g =$	$\frac{Q_g}{A_t} =$	$\frac{94.40}{1.00} =$	94.4	m/s
---------------------------------	---------------------	------------------------	------	-----

Inertial impaction parameter, $\Psi = \frac{C \rho_p v_g (d_p)^2}{18 d_d \mu}$

Calculating Ψ in terms of d_p , $\Psi = \frac{C \times 700 \times 94.4 \times (d_p \times 10^{-6})^2}{18 \times 0.0001 \times 0.0000252}$

For $d_p = 2.5 \mu\text{m}$, $\Psi = 1.61 d_p^2$ for $C = 1.105$

$\Psi = 1.46 d_p^2$ for $C = 1.000$

SQRT(Ψ) = 1.269 d_p for $C = 1.105$

SQRT(Ψ) = 1.207 d_p for $C = 1.000$

R = liquid flow rate m^3 / m^3 of gas = $Q_L / Q_g = 0.13 / 94.4$

R = 0.00138

Efficiency, $\eta = 1 - e^{-\kappa R \sqrt{\psi}}$	$\therefore \kappa R \sqrt{\psi} =$	0.349 dp	for C = 1.105
	$\kappa R \sqrt{\psi} =$	0.332 dp	for C = 1.000
=	$1 - \text{EXP}(-0.349dp)$	for C =	1.105
=	$1 - \text{EXP}(0.332dp)$	for C =	1.000
Efficiency calculation for dp =	2.5 μm		
=	$1 - \text{EXP}(-0.349 \times 2.5)$		
=	58.26%	Mass efficiency =	$0.58 \times 25 / 10$ 14.56%
Efficiency calculation for dp =	15 μm		
=	$1 - \text{EXP}(-0.332 \times 15)$		
=	99.32%	Mass efficiency =	$0.99 \times 15 / 10$ 14.90%

Average diameter (μm)	% of total	Efficiency (%)	Mass Efficiency (%)
2.5	25	58.26	14.56
7.5	20	91.74	18.35
15	15	99.32	14.90
25	15	99.98	15.00
35	10	100.00	10.00
50	15	100.00	15.00
$\Sigma =$			87.81
Overall removal efficiency \approx	88%	ANS.	

Example 9: Calculate the venturi throat area for a wet scrubber required to achieve 95% percent removal of a 1.50- μm -radius particle having a density of 1,350 kg/m^3 for the following gas stream and venturi characteristics.

Gas flow rate = 13.0 m^3/s ; Gas temperature 175 $^{\circ}\text{C}$; Droplet diameter = 110 μm ; Liquid flow rate = 0.150 m^3/s ; Coefficient, k = 200.

Example 9: Solutions

Data Given,				
Particle diameter, d_p	=	3.00	$\mu\text{m} =$	0.000003 m
Particle density, ρ_p	=	1350	kg/m^3	
Throat area, A_t	=	???	m^2	
Gas flow rate, Q_g	=	13.00	m^3/s	
Gas temperature, T_g	=	175	$^{\circ}\text{C} =$	448 K
Efficiency, η	=	95%		
Liquid flow rate, Q_L	=	0.15	m^3/s	
Coefficient, κ	=	200		
Water droplet diameter, d_d	=	110	$\mu\text{m} =$	0.00011 m
Viscosity of gas, μ	=	2.650E-05	Pa.s (From Table A-4 or literature)	

Cunningham correction factor, $C = 1 + \frac{6.21 \times 10^{-4} (T)}{d_p} = 1 + \frac{6.21 \times 10^{-4} (448)}{3.00} = 1.093$

R	=	liquid flow rate m^3 / m^3 of gas =	$Q_L/Q_g = 0.15/13$
			= 0.01154
Efficiency, η	=	$1 - e^{-\kappa R \sqrt{\psi}}$	
0.95	=	1 - EXP(-200x0.0115384615384615xSQRT(zhai))	
Ψ	=	$\frac{[\ln(1 - \eta)]^2}{(\kappa R)^2}$	
	=	$\frac{[\ln(1 - 0.95)]^2}{200 \times 0.0115384615384615^2}$	
	=	1.685	

Inertial impaction parameter, $\Psi = \frac{C\rho_p v_g (d_p)^2}{18d_d \mu}$				
	$v_g = \frac{18 d_d \mu \Psi}{C\rho_p (d_p)^2}$			
	$= \frac{18 \times 0.00011 \times 2.65022373188406E-05 \times 1.6852}{1.093 \times 1350 \times (0.000003)^2}$			
	$= 6.660$ m/s			
Venturi throat area, $A_t = \frac{Q_g}{v_g}$	$= \frac{13.00}{6.660}$	$=$	1.95 m ²	ANSI

Electrostatic Precipitator (ESP)

High efficiency, dry collection of particles from hot gas stream can be obtained from electrostatic precipitation of the particles. The ESP is usually constructed with alternating plates and wires. A large direct current potential (30-75kV) is established between the plates and wires. This results in creation of an ion field between the plate and wire, ions attached to the particles, giving them a net negative charge. Figure 31 shows electrostatic precipitators with tube (left) and plate (right).

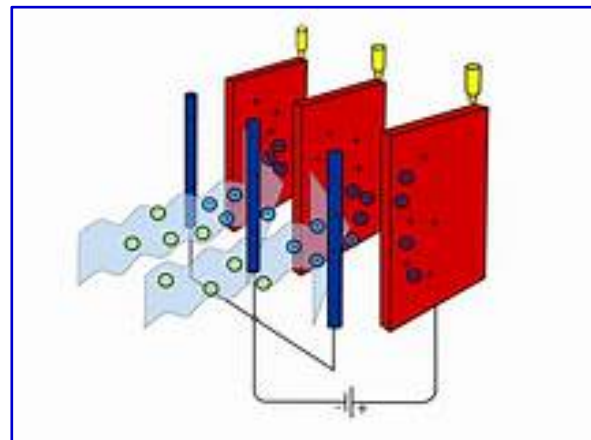


Figure 30: Electrostatic precipitators with tube (left) and plate (right)

The particles then migrate toward the positively charged plate where they stick (Figure 32). The plates are then rapped at frequent intervals and the agglomerated sheet of particles falls to a hopper. ESPs have been used to control air pollution from electric power plants, Portland cement kilns, blast furnace gas, kilns and roasters from metallurgical processes, and mist from acid production facilities. An example of ESP sue in a power plant is shown in Figure 33.

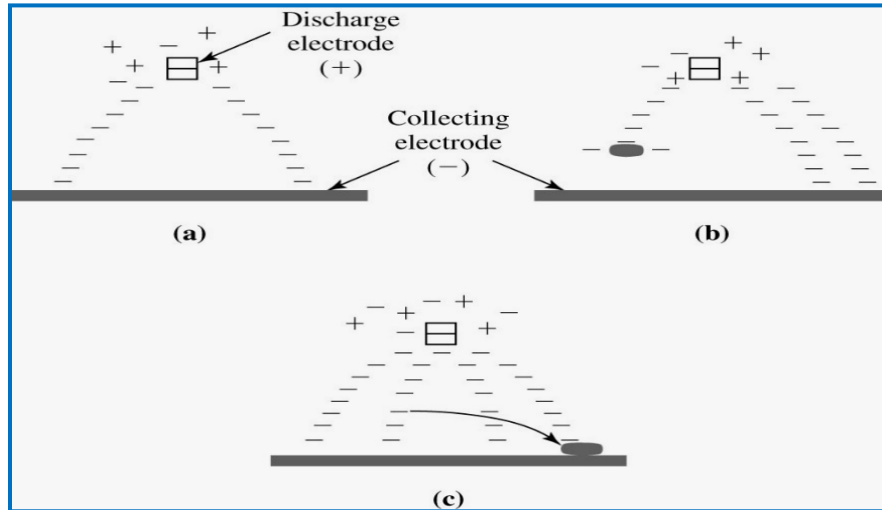


Figure 31: Particle charging and collecting in ESP



Figure 32: Electrostatic precipitators (ESPs) in service in a power plant

Example 10: Determine the collection efficiency of an electrostatic precipitator (ESP) tube that is 0.30 m in diameter and 2.0 m in length for particles that are 1.0- μm in diameter. The flow rate is 0.150 m^3/s , the collection field intensity is 100,000 V/m, the particle charge is 0.300 femtocoulombs (fC), and the gas temperature is 25°C.

Example 10: Solutions

Collection field intensity, $E_p =$	100,000	V/m		
Gas flow rate, $Q_g =$	0.15	m ³ /s		
Gas temperature, $T_g =$	25	°C =	298	K
Efficiency, $\eta =$?			
Viscosity of air, $\mu =$	1.850E-05	Pa.s (Table A-4 or literature)		
Charge, $q =$	0.300	fC =	3E-16	C
ESP tube length, L =	2.000	m		
ESP tube diameter, D =	0.300	m		

Cunningham correction factor, $C = 1 + \frac{6.21 \times 10^{-4} (T)}{d_p} = 1 + \frac{6.21 \times 10^{-4} (298)}{1.00} = 1.185$

Migration velocity, $w =$	$\frac{qE_p C}{6\pi r \mu}$			
		$= \frac{0.000000000000000003 \times 100000 \times 1.185}{6 \times 3.14159 \times (0.5/1000000) \times 0.0000185}$		
		$= 0.204$	m/s	

Tube surface area, A =	$3.14159 \times D \times L =$	$3.14159 \times 0.3 \times 2 =$	1.885	m ²
	$\eta = 1 - e^{-Aw/Q_g}$			
	$= 1 - \text{EXP}(-1.885 \times 0.204/0.15) =$		92.29%	ANS.

Example 11: Design a "standard" ESP (tubes) having a removal efficiency of 85% to remove particles that are 1.0-µm in diameter. The flow rate is 0.150 m³/s, the collection field intensity is 100,000 V/m, the particle charge is 0.300 femtocoulombs (fC), and the gas temperature is 25°C.

Example 11: Solutions

Particle diameter, $d_p =$	1.00	µm, r =	0.5	µm
Collection field intensity, $E_p =$	100,000	V/m		
Gas flow rate, $Q_g =$	0.15	m ³ /s		
Gas temperature, $T_g =$	25	°C =	298	K
Efficiency, $\eta =$	85%			
Viscosity of air, $\mu =$	1.844E-05	Pa.s (Table A-4 or literature)		
Charge, $q =$	0.300	fC =	3E-16	C

Cunningham correction factor, $C = 1 + \frac{6.21 \times 10^{-4} (T)}{d_p} = 1 + \frac{6.21 \times 10^{-4} (298)}{1.00} = 1.185$

Migration velocity,	$w = \frac{qE_p C}{6\pi r \mu}$				
		$= \frac{0.0000000000000003 \times 100000 \times 1.185}{6 \times 3.14159 \times (0.5/1000000) \times 0.00001844}$			
		$= 0.205$	m/s		

Using the efficiency equation, $\eta = 1 - e^{-Aw/Q_g}$

$0.85 = 1 - \text{EXP}(-A \times 0.205 / 0.15)$	
$A = -0.15 \ln(1 - 0.85) / 0.205$	
$= 1.391$	m ²

Combination of tube diameter and length			
Diameter, d (m)	Length, L (m)	Area provided (m ²)	Comment
1.00	0.443	1.391	OK
0.50	0.886	1.391	OK
0.25	1.771	1.391	OK

13.3 Flue Gas Desulfurization

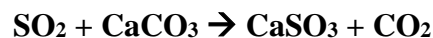
Flue gas desulfurization (FGD) systems fall into two broad categories:

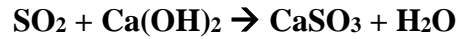
- Nonregenerative
- Regenerative

Nonregenerative means that the reagent used to remove sulfur oxides from the gas stream is used and discarded. **Regenerative** means that the reagent is recovered and reused. In terms of the number and size of systems installed, nonregenerative systems dominate.

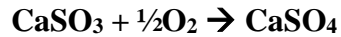
Nonregenerative Systems:

There are **9 commercial nonregenerative** systems. All have reaction chemistries based on lime (CaO), caustic soda (NaOH), soda ash (Na₂CO₃), or ammonia (NH₃). The SO₂ removed in a lime/limestone-based FGD system is converted to sulfite. The overall reactions are as follows:





Part of the sulfite is oxidized with the oxygen content in the flue gas to form sulfate:



13.4 Control Technologies for Nitrogen Oxides

Almost all nitrogen oxide (NO_x) air pollution results from combustion processes. They are produced from the oxidation of nitrogen bound in the fuel, from the reaction of **molecular oxygen** and nitrogen in the combustion air temperature above **1,600 K** ($\text{N}_2 + \text{O}_2 \leftrightarrow 2\text{NO}$) and from the reaction of nitrogen in the combustion air with hydrocarbon radicals.

Control technologies are grouped into **2 categories**:

1. those that prevent the formation of NO_x during combustion processes (Prevention).
2. those that convert the formed NO_x during combustion into nitrogen and oxygen (Post-Combustion).

Prevention

The processes in this category employ the fact that reduction of peak flame temperature in the combustion zone reduces **NO_x** formation. Nine alternatives are available:

1. minimizing operating temperature
2. fuel switching
3. low excess air
4. flue gas recirculation
5. lean combustion
6. staged combustion
7. low NO_x burner
8. secondary combustion
9. water/steam injection

Post-Combustion

Three processes may be used to convert **NO_x** to nitrogen gas:

1. Selective catalytic reduction (SCR),
2. Selective noncatalytic reduction (SNCR), and

3. Nonselective catalytic reduction (NSCR)

SCR: This process uses a catalyst bed (*usually vanadium-titanium, or platinum based and zeolite*) and anhydrous ammonia (NH_3). After the combustion process, ammonia is injected upstream of the catalyst bed. The NO_x reacts with the ammonia in the catalyst bed to form N_2 and water.

SNCR: In this process, ammonia or urea is injected into the flue gas at an appropriate temperature (870 to 1,090°C). The urea is converted to ammonia, which reacts to reduce NO_x to N_2 and water.

NSCR: This process uses three-way catalyst similar to that used in automotive applications. In addition to NO_x control, hydrocarbons and CO are converted to CO_2 and water. These systems require a reducing agent similar to CO and hydrocarbons upstream of the catalyst.

14. Summary

In this course Physical and Chemical Fundamentals such as Ideal Gas Law, Dalton’s Law and Partial Pressure; Adiabatic Expansion and Compression; Units of Measure; Air Pollution Perspective; Air Pollution Standards; Effects of Air Pollutants on Materials, Vegetation, and Health; Origin and Fate of Air Pollutants such as Carbon Monoxide, Hazardous Air Pollutants (HAPs), Lead, Nitrogen Dioxide, Photochemical Oxidants, Sulfur Oxides and Particulates; Micro and Macro Air Pollution; Contemporary Issues such as Acid Rain, Ozone Depletion, Greenhouse Effect; Impacts of Engineering Solutions in Global, Economic, Environmental and Societal Context; Air Pollution Meteorology such as the Atmospheric Engine, Turbulence, Stability, and Terrain Effects; Atmospheric Dispersion, Factors Affecting Dispersion of Air Pollutants, and Dispersion Modeling; Indoor Air Quality Model; Air Pollution Control of Stationary Sources such as Gaseous Pollutants, Flue Gas Desulfurization, Control Technologies for Nitrogen Oxides, and Particulate are discussed and elaborated. Several problems on unit conversion, pollutant dispersion, air pollution control device design and efficiency estimation were solved to understand the extent of air pollution and its control.

15. References

1. Personal work experience and open sources from internet.
2. Other references are shown as footnotes.

+++++ **The End** +++++

Any questions please contact the instructor at makarim@juno.com

And copy info@pdhnow.com

QUIZ for Principles of Air Pollution and Control (* Answer Key)

1. The **1970 Clean Air Act (CAA)** required USEPA to investigate and describe the environmental effects of any air pollutant emitted by stationary or mobile sources that may adversely affect human or the environment. The USEPA used these studies to establish the NAAQS. The NAAQS stands for:

- a. National Ambient Air Quality Standards
- b. National Aeronautic Air Quality Standards
- c. National Ambient Air Quality Systems
- d. National Aeronautic Auto Quality Standards

2. The five primary criteria pollutants are:

- a. CO, NO₂, SO₂, PM₁₀, and Particulate Lead
- b. CO, NO₂, SO₂, PM₁₀, and Ozone
- c. CO, NO₃, SO₂, PM₁₀, and Particulate Lead
- d. CO, NO₂, SO₃, PM₁₀, and Ozone
- e. CO₂, NO₂, SO₂, PM₁₀, and Particulate Lead

3. Under 1970 CAA, USEPA was directed to establish regulations for *hazardous air pollutants (HAPs)* using a risk-based approach. These are called **NESHAPs** and NESHAPs stands for:

- a. National Emission Systems for Hazardous Air Pollutants
- b. National Emission Standards for Hazardous Air Pollutants
- c. National Emerging Standards for Hazardous Air Pollutants
- d. National Emission Standards for Hazardous Aeronautic Pollutants

4. The primary standard for air pollutants was established to protect human health with an _____.

- a. adequate margin of safety
- b. adequate margin of pollution
- c. standard margin of pollution
- d. sufficient amount of safety.

5. Air pollutants have effects on _____, and _____.

- a. Materials, Vegetation, and Health
- b. Water, Soil, and Tree
- c. All of the above
- d. None of the above.

6. Solid particles of large enough size and traveling at high enough speed can cause deterioration by _____.

- a. abrasion
- b. scrapping
- c. scratching
- d. snatching.

7. Factors that influence deterioration of materials by air pollutants are: _____, _____, _____, and _____.
- moisture, temperature, sunlight, and position of the exposed material
 - moisture and temperature
 - sunlight and position of the exposed material
 - moisture, temperature, and sunlight.
8. Combinations of pollutants that alone cause no damage are known to produce acute effects when combined. This effect is known as _____.
- synergism
 - catabolism
 - metabolism
 - anabolism.
9. Air pollutants have two types of effects on health and these are _____ and _____.
- severe and non-chronic effect
 - acute and non-chronic effect
 - acute and chronic effect
 - non-acute and chronic effect
10. Mercury attacks the brain, kidneys, and bowels. Other potential effects from the HAPs are birth defects and damage to the immune and nervous systems.
- True
 - False.
11. Chronic exposure to lead may result in brain damage characterized by seizures, mental incompetence, and active aggressive behavior.
- True
 - False.
12. Exposure to **NO₂** concentrations above 5 ppm for 15 minutes results in _____ and _____ of the respiratory tract.
- cough, irritation
 - cough, fever
 - cancer, irritation
 - cancer, fever.
13. Higher levels of _____ increase risk of respiratory, cardiovascular, and cancer related deaths, as well as, pneumonia, lung function loss, and asthma.
- PM_{2.5}
 - PM₁₀
 - PM₁₅
 - PM₂₀.

14. Ozone is the principal photochemical oxidant. Its formation is usually attributed to the nitrogen photolytic cycle. Hydrocarbons modify this cycle by reacting with atomic oxygen to form free radicals (highly reactive organic species).

- a. True
- b. False.

15. Unpolluted rain is naturally acidic because CO₂ from the atmosphere dissolves to a sufficient extent to form carbonic acid.

- a. True
- b. False.

16. Without ozone in the stratosphere, every living thing in the earth's surface would be incinerated, although on the other hand, ozone can be lethal.

- a. True
- b. False.

17. The highs and lows depicted on weather maps are simply areas of _____ and _____ pressure.

- a. greater and lesser
- b. large and small
- c. all of the above
- d. none of the above.

18. The elliptical lines showed in the weather maps represent the lines of _____ _____ or _____.

- a. constant pressure or isobars
- b. constant height or elevations
- c. constant temperature or isothermals
- d. constant sunlight or isosolar.

19. The technical names given to the atmospheric engine systems are *anticyclones* for highs and *cyclones* for lows. Anticyclones are associated with _____ _____ and cycles are with _____ _____

- a. good weather; foul/bad weather
- b. good temperature; foul/bad temperature
- c. good pressure; foul/bad pressure
- d. good sunlight; foul/bad sunlight.

20. _____ and _____ are the foulest of the cyclones.

- a. Tornadoes and hurricanes
- b. Stable and unstable
- c. Neutral and unstable
- d. All of the above
- e. None of the above.

21. The tendency of the atmosphere to resist or enhance vertical motion is termed as *stability*.

- a. True
- b. False.

22. The stability is related to both wind speed and the change in air temperature with height (*lapse rate*). There are 3 stability categories, and these are:

- a. Neutral
- b. Stable
- c. Unstable
- d. All of the above
- e. None of the above.

23. When there is no change in temperature with elevation, the lapse rate is called inversion. Inversion is the most severe form of a stable temperature profile. It is often associated with restricted air volumes that cause air pollution episodes.

- a. True
- b. False.

24. When the temperature increases with elevation, the lapse rate is called isothermal.

- a. True
- b. False.

25. A dispersion model is a mathematical description of the meteorological transport and dispersion process that is quantified in terms of source and meteorological parameters during a particular time.

- a. True
- b. False.

26. The control devices/technologies used to control gaseous air pollutants from stationary sources are based on the principle of.

- a. Absorption
- b. Adsorption
- c. Combustion
- d. All of the above
- e. None of the above.

27. For controlling particulate pollutants the following control devices are used and these are:

- a. Cyclones, Filters, Liquid scrubbing, and Electrostatic precipitator (ESP)
- b. Cyclones, Filters, Adsorption, and Liquid scrubbing
- c. Cyclones, Filters, Absorption, and Electrostatic precipitator (ESP)
- d. Filters, Liquid scrubbing, Combustion, and Electrostatic precipitator (ESP).

28. Adsorption is a mass transfer process in which the gas is bonded to a solid. It is an interface phenomenon. The gas called _____ penetrates into the pores of the solid called the _____ but into the lattice itself.

- a. adsorbate; adsorbent
- b. solvent; solute
- c. solid; liquid
- d. liquid; gas.

29. The most common adsorbents are _____, _____, _____, _____, _____.

- a. activated charcoal
- b. molecular sieves
- c. silica gel
- d. the activated alumina
- e. all of the above
- f. none of the above.

30. Combustion is a possible alternative when the contaminant in the gas stream is _____ to an inert gas.

- a. decomposable
- b. oxidizable
- c. combustible
- d. all of the above
- e. none of the above.

31. In absorption process, the removal of the pollutant gas takes place in the following steps:

- a. Diffusion of pollutant gas to the surface of the liquid
- b. Transfer across the gas/liquid interface (dissolution)
- c. Diffusion of the dissolved gas away from the interface into the liquid
- d. All of the above
- e. None of the above.

32. There is one secondary criteria pollutant which is.

- a. CO
- b. NO₂
- c. SO₂
- d. Ozone.

33. One of the control devices/technologies used to control gaseous air pollutants from stationary sources are based on the **principle** of:

- a. separation
- b. adsorption
- c. diffusion
- d. percolation

34. One of the control devices/technologies that is NOT used to control gaseous air pollutants from stationary sources are based on the **principle** of:
- absorption
 - adsorption
 - diffusion
 - combustion
35. One of the control devices/technologies used to control particulate air pollutants from stationary sources is:
- cyclone
 - absorption
 - adsorption
 - combustion
36. One of the control devices/technologies that is NOT used to control particulate air pollutants from stationary sources is:
- cyclone
 - adsorption
 - filter
 - liquid scrubber
37. Flue gas desulfurization (**FGD**) systems fall into the following broad categories:
- Nonregenerative
 - Regenerative
 - All of the above
 - None of the above
38. The control devices/technologies that is used to control particulate air pollutants from stationary sources are:
- cyclone
 - electrostatic precipitator
 - liquid scrubber
 - all of the above
 - none of the above
39. During adsorption process, the removal of the gaseous pollutants takes place in steps and these are/is:
- diffusion of pollutant gas to the surface of the liquid
 - transfer across the gas/liquid interface (dissolution)
 - diffusion of the dissolved gas away from the interface into the liquid
 - all of the above
 - none of the above

40. Control technologies that used to control nitrogen oxides are grouped into:
- a. those that prevent the formation of NO_x during combustion processes
 - b. those that convert the formed NO_x during combustion into nitrogen and oxygen
 - c. all of the above
 - d. none of the above