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التلوث البيئي والسلامة في مصافي النفط

م.د. جنان النجار

Environmental Pollution in Petroleum Refineries

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1. Introduction

Environment

The sum total of water, air and land and the inter-relationships that exist among them and with the human beings, other living organisms and materials. The concept of environment can be clearly understood from Fig. 1

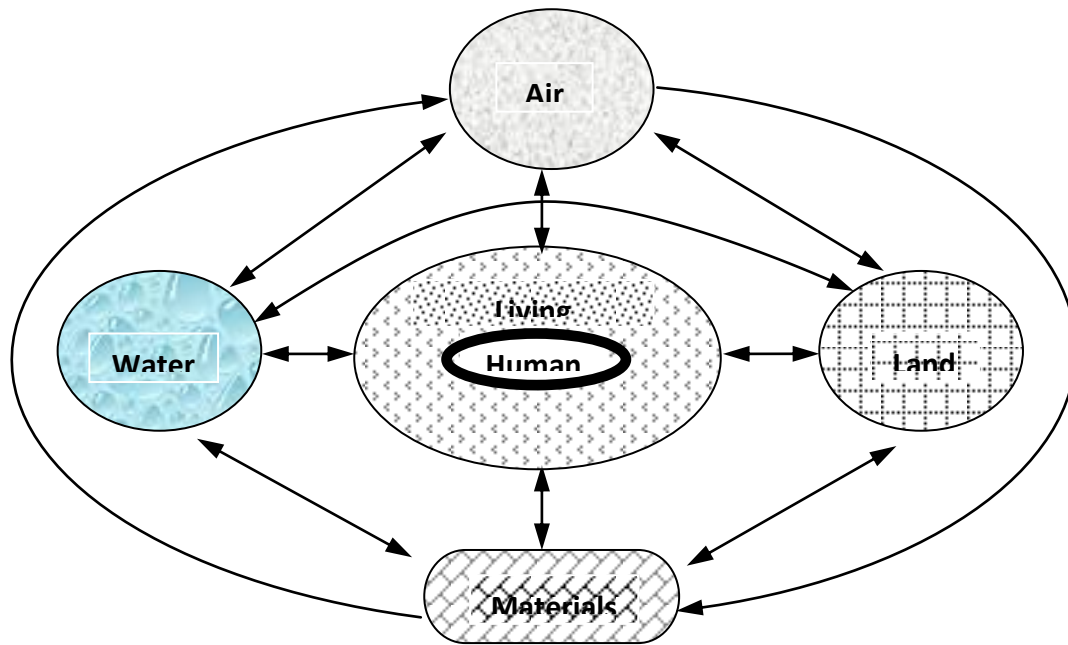


Fig.1 Concept of Environment: air, water, living organisms and materials surrounding us and their interactions together constitute environment

Environmental Engineering

Environmental engineering is the integration of science and engineering principle to:

- improve the natural environment,
- provide healthy water, air, and land for human habitation and for other organisms,
- Clean up pollution sites.

Environmental pollution

Pollution is the introduction of contaminants substance (gas, liquid, solid or mix.) or energy (heat, light, noise, or radiation) into environment that cause damage and undesirable change in the physical, chemical, biological characteristics of the air, water, or land which then affect the health, survival or activities of human and other living organisms.

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Pollutants

A pollutant is any substance that causes pollution. Pollutants may be chemical, biological, thermal, radioactive or even mechanical (dust, sediment, grit, etc.). A pollutant has also been defined as any solid, liquid, or gaseous substance present in such concentration as may be or tend to be injurious to the environment. These pollutants may be introduced into environment naturally or by human activity. One of the source emissions of pollutant into environments is the petroleum refinery

Petroleum Refining

Petroleum refining can be defined as the physical, thermal and chemical separation of crude oil into the major distillation components or fractions. These distillation fractions can be further processed through separation and conversion into finished useful petroleum products such as petroleum naphtha, gasoline, diesel fuel, fuel asphalt base, heating oil, kerosene and liquefied petroleum gas.

These products can be broadly grouped into three areas:

- Fuels (such as motor gasoline, diesel fuel, aviation fuel, light and heavy fuel oil).
- Non-fuel products (such as lubricating oils and greases, asphalt)
- Raw materials for the chemical industry.

Pollutants emitted from petroleum refinery

Refineries and petrochemical process are responsible for emission of many pollutants both the air and into the water:

❖ Pollutants emission into the air:

- Sulfur Oxides SO_x
- Nitrous oxides NO_x
- Carbon dioxide CO_2
- Carbon Monoxide CO
- Volatile Organic Compounds (VOC)
- Particulate matter

❖ Pollutants emission into the water:

- waste water from petroleum industries containing:
Organic compounds, phenols, toxic metals and other pollutants such as iron, dissolved and suspended solids, oil, cyanides, sulfides and chlorine.

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Environmental impact of the petroleum industry

The environmental impact of the petroleum industry is often negative because it is toxic to almost all forms of life. The possibility of climate change exists. The following impacts:

1. **Toxicity:** crude oil is a mixture of many different kinds of organic compound, many of which are highly toxic and cancer.
2. **Exhaust:** exhaust gas or flue gas is emitted as a result of combustion of oil or petroleum distillates; usually the combustion is not complete. It is discharge into the atmosphere through an exhaust pipe or flue gas stack. The most combustion gas is nitrogen N_2 , water vapor H_2O , and carbon dioxide, these gases are not toxic (although CO_2 is a greenhouse gases that contributes to global warming). Also some of combustion gas is toxic such as carbon monoxide CO .
3. **Acid rain:** High temperatures created by the combustion of petroleum causes nitrogen gas in the surrounding air to oxidize, creating nitrous oxides. Nitrous oxides, along with sulfur dioxide from the sulfur in the oil, combine with water in the atmosphere to create acid rain. Acid rain causes many problems such as dead trees and acidified lakes with dead fish. Coral reefs (الشعاب المرجانية) in the world's oceans are killed by acidic water caused by acid rain.
4. **Climate change:** Humans burning large amounts of petroleum create large amounts of CO_2 (carbon dioxide) gas that traps heat in the earth's atmosphere. Also some organic compounds, such as methane released from petroleum drilling or from the petroleum itself, trap heat several times more efficiently than CO_2 .
5. **Oil spills:** An oil spill is the release of a [liquid petroleum hydrocarbon](#) into the environment, especially marine areas, due to human activity, and is a form of pollution.
6. **Volatile organic:** (VOCs) are gases or vapors emitted by various solids and liquids, many of which have short- and long-term adverse effects on human health and the environment. VOCs from the petroleum are toxic and foul air, and some like benzene are extremely toxic, carcinogenic and cause DNA damage.

Type of pollution

The major categories of pollution are:

- | | | |
|--------------------|---------------------|---------------------------|
| 1) Water pollution | 3) Soil pollution, | 5) Groundwater pollution. |
| 2) Air pollution, | 4) Ocean pollution. | |

The Impact of Production Operations

Many of the materials and wastes associated with drilling and production activities have the potential to impact the environment. The potential impact depends primarily on:

1. the concentration of material after release
2. the biotic community that exposed to material

The most common measure of the potential environmental impact of a material is its toxicity. Toxicity occurs when materials cause a deleterious effect on an organism, population, or community. These effects can range from temporary disorientation to lethality.

1. Measuring toxicity

Toxicity is determined through bioassay by exposing laboratory animals to different amount of the toxic substance.

Two types of toxicity measurements are commonly used:

- Dose
- Concentration

Dose: Is the concentration of a substance that has been absorbed into the tissue of the test species. The dose is the mass fraction of the substance in the animal tissue (milligram of substance per gram of tissue, mg/g) when a particular effect has been observed. The following dose expression used:

1. LD₅₀: A dose that is lethal to 50% of the animals
2. LDLO : The lowest dose that is lethal

Concentration: Is the measure the concentration of a substance in the environment that the species live in. The concentration is the fraction of the substance in air or water that causes a particular effect when the target animals are placed in that environment. It is normally given either as a mass fraction in part per million (ppm) or as mass per unit volume (mg/l). The following concentration expression used:

1. LC₅₀: A lethal concentration that kills 50% of the animals within a given period of time.
2. LCLO: The lowest lethal concentration for the same period of time.

Concentration is the toxicity measure most commonly used for materials associated with the petroleum industry.

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2. Hydrocarbons

Hydrocarbon

Crude oil contains thousands of different kinds of hydrocarbon molecules. The toxicities and environmental effects of different molecules vary considerably. Crude oil can also contain Significant quantities of other elements, like sulfur, nitrogen, oxygen, and heavy metals, further complicated its characterization. Crude oil is typically composed as following:

(50-98) hydrocarbons

(0-10) sulfur

(0-1%) nitrogen

(0-5 %) oxygen

(ppm) heavy metals

Table 1 summarizes most of the families of hydrocarbon found in the crude oil.

Table.1 Families of Hydrocarbons

Family Name	Examples	Formula
Alkanes	Methane	CH ₄
	Ethane	C ₂ H ₆
	propane	C ₃ H ₈
Alkenes (Olefin)	Ethylene	C ₂ H ₄
	Propylene	C ₃ H ₆
Alkynes (acetylenes)	Ethyne	C ₂ H ₂
	Propyne	C ₃ H ₄
Cyclic alkanes (naphthenes, cycloparaffines)	Cyclopropane	C ₃ H ₆
	cyclobutane	C ₄ H ₈
Aromatics	Benzene	C ₆ H ₆
	Toluene	C ₆ H ₅ CH ₃
Polyaromatics	Naphthalene	C ₁₀ H ₈
	Tetralin	C ₁₀ H ₁₂
Alcohols	Methanol	CH ₃ OH
	Ethanol	C ₂ H ₅ OH
Acids	Acetic acid	C ₂ H ₄ OH
Amines	Methylamine	CH ₃ NH ₂

Hydrocarbon Toxicity

The factors that affect the toxicity of hydrocarbons include:

❖ molecular weight and hydrocarbon family, as following:

1. For the hydrocarbon of similar type (the same family) the toxicity tends to increase with decreasing molecular weight. Smaller molecules more toxic than larger molecules. Light crude oils and refined more toxic than heavy crude oils

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2. For the similar molecular weight hydrocarbons the toxicity varies with family. The toxicity of hydrocarbons family generally increases in the following order: alkanes, alkenes, alkenes, and cycloparaffins, aromatics, and polyaromatics hydrocarbons.
- ❖ An important factor affecting the toxicity of crude oils is their history before any organisms are exposed: The toxicity of crude oils decreases with increasing the time because the most toxic hydrocarbon (the most volatile) rapidly evaporated from released site. Within a few days after a crude oil release, only higher molecular weight hydrocarbon remains, so the toxicity of the remaining crude oils is lower.

Environmental Impact of Hydrocarbons

The hydrocarbon impact on:

1. Marine animals
2. Human health
3. Plant growth when release on land

3. Salt (Sodium chloride)

Salt in low concentration is essential to the health of plants and animals. At concentration different from naturally occurring levels, salt can cause an adverse impact:

- ❖ Impact on plants: The increase of salt concentration cause the following:
 - Disruption of the fluid chemistry balance within cells.
 - Salt can indirectly impact plant growth by altering the physical properties of the soil.
- ❖ Impact on aquatic organisms

The discharge of water having a higher salt content can impact the aquatic organisms

Salinity measurements

A number way for measuring the salinity of soil, these include measuring:

- 1- The electrical conductivity (EC) of a solution: this includes the measure of the total amount of cations and anions dissolved in water. These ions can include sodium (Na), Calcium (Ca), magnesium (mg), potassium (K), chloride (Cl), sulfate (SO₄), bicarbonate (HCO₃), carbonate (CO₃) and hydroxide (OH).
- 2- Total dissolved solid (TDS): is the weight of residue after all the water has been evaporated.

The EC is related to TDS. The relationship between EC and TDS is given as follows:

$$TDS = A * EC$$

where A = 640 is an empirical constant (cm.mg/mmhos.liter)
EC (mmhos/cm)

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The most common impact of brine on plants is that it increases the osmotic pressure of the soil solution.

Osmosis is the process that controls the movement of water between solutions, with water following from lower to higher osmotic pressure.

If the osmotic pressure of the soil solution outside the plant exceeds that inside the cell, water cannot flow into the plant.

The osmotic pressure (OP) is related to the EC through the following equation:

$$OP = 0.36 * EC$$

The osmotic pressure (OP) is in the atmospheres and the electrical conductivity in mmhos / cm.

4. Heavy Metals

Heavy metals encountered in drilling and production activities are related to a variety of environmental concern, depending on the metal and its concentration. At very low concentration some metals are essential to healthy cellular activities. Essential metals include chromium, cobalt, copper, iodine, iron, manganese, molybdenum, nickel, selenium, silicone, vanadium and zinc. At higher concentration, however, metals can be toxic.

5. Production Chemicals

The various chemicals used during production have a widely varying potential for environmental impact, depending on the chemical and its concentration. These chemicals such as:

1. Acids
2. Pesticides
3. Biocides: such as aldehydes, formaldehydes mixtures, amine and amine salts, etc.
4. Scale inhibitor: such as Amine phosphate ester, phosphonate
5. Emulsion breakers: such as phenol formaldehydes, etc.....
6. Corrosion inhibitors: such as ammonium salts, amines, sulfonate, ammonium bisulfate and sodium sulfate...etc....

6. Produced water

Produced water is a term used in the oil industry to describe water that is produced as a byproduct along with the oil and gas. Oil and gas reservoirs often have water as well as hydrocarbons, sometimes in a zone that lies under the hydrocarbons, and sometimes in the same zone with the oil and gas. The potential for environmental impacts following the discharge of produced water arises primarily from:

1. Its high salts content
2. Its heavy metals content
3. Its dissolved or suspended hydrocarbons
4. Its oxygen deficiency

Water and Wastewater Treatment

Water

Water is the most abundant chemical component in the biosphere. It is important to all life on the earth including human life.

Source of water

The main sources of water are:

1. **Ground water:** is the water that has percolated (ترشح) downward from the ground surface through the soil pores. Water is normally withdrawn from these reservoirs by well.
2. **Surface water:** All water on the surface of the Earth including lakes, ponds, rivers, streams and rainfall water. It is important source of public water supplies because of high withdrawn rates. Surface water supplies are not reliable (مضوق) as groundwater sources because the surface water is restricted by various sources of pollution, such as industrial and municipal wastes. Direct use of rainfall water is limited but it is important water source in a few areas.
3. **Sea water:** it is a valuable in unlimited quantities. This can be converted into fresh water by a number of processes. Conversion cost is 2 to 5 times higher than these of treating fresh water. Desalination is term used for removal of dissolved salts from water.
4. **Reclaimed wastewater:** is the water that has been treated sufficiently for direct reuse in industry and agriculture and for limited municipal application.

Utilization of water

The most important utilization are:

1. Irrigation: the amount of water required for irrigation purpose various with climate of region and the type of crops that are raised.
2. Domestic water supply: the requirements vary from season to season and from rural to urban areas.
3. Power generation: cooling is principle water use in thermal power generation and more than 99% of water used is required for condenser cooling.
4. Industrial water use: industry is much dependent on adequate water supply. The enormous demand of industry for water is obvious such as H_2SO_4 production, oil refinery, milk products, etc.

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Types of water pollutants and their effects

The main pollutants in water are:

1. Oxygen demanding wastes:

Biological waste like food waste, dead plant, and animal tissue that consumed oxygen dissolved in water during its degradation by bacteria, thus oxygen required for survival of fish, other marine animals, and marine plants.

a- Dissolved oxygen, DO:

Dissolved oxygen is the amount of oxygen dissolved in water to sustain the plant and animal life in any aquatic system.

b- Biochemical oxygen demand, BOD:

BOD is the measurement of the amount of oxygen utilized by microorganisms during oxidation of organic material. It is the most widely known measurement for assessing the water pollution by a given organic waste.

2. pathogens:

Pathogens are a disease causing agents. Water is a potential carrier of pathogenic microorganisms. These pathogens are carried into the water bodies by sewage and waste from farms and various industries.

3. Refractory organic compounds:

These include pesticides, herbicides, phenols, synthetic organic chemical and detergents. These compounds in contrast to the organic waste are not biodegradable and may persist for a long periods.

4. Nutrients:

Nutrients are the chemical material required to growth of aquatic life, Such as nitrogen and phosphorus. Nitrogen and phosphorus enter the water bodies directly from the manufacture and use of fertilizers and from the processing of biological material such as food and textiles. When large concentrations of nutrient are present in water, an excess growth of algae known as algae bloom appears. This produces an unsightly green slime layer over the surface of water body lead to eutrophication.

5. Inorganic chemical:

These include inorganic salts, mineral acids, and heavy metal compounds. Most of these are toxic and are capable of killing living organisms in the water bodies.

6. sediments:

These include soil, sand, and mineral particles or pulverized coal ash. Their effects increasing turbidity and consequently of reducing the amount of sunlight available to water plants.

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7. Radioactive substances:

Radioactive substances include radioactive material and radioactive waste. The refining of uranium is the most important source of radioactive waste producing radium, bismuth, etc. Radioactive substances can enter human with food and water and accumulated in blood, liver, muscular tissues (انس جوع مضايه) causing to serious of health problem to human kinds.

8. Thermal pollution

Power plant and industry use large quantities of water for cooling purpose. This could results in increase in the temperature of the water bodies and causing decrease in the percentage of dissolved oxygen in the aquatic media and then decreases in the saturation percentage.

9. Oils:

Oils are important commodity and virtual for every human activity now. Oil wastes enter rivers and other water bodies from several sources like industrial effluents, oil refineries, storage tank, automobile waste oil, and petrochemical plants. Oil insoluble in water so it floats and spread rapidly into a thin layer. The lighter low molecular-weight elements, which are most toxic to organism, evaporate at slow rate effects on life in the water.

Oxygen demanding waste

Dissolved oxygen (DO)

Dissolved is essential for sustaining the plant and animal life in any aquatic system. There are four processes which actually affected the DO content:

- Reaeration
- Photosynthesis (تخليق ضوئي)
- Respiration (تنفس)
- Oxidation

Reaeration

Reaeration is the process of oxygen transfer form atmosphere to water.

The solubility of oxygen in fresh water at saturation point decreases with an increase in temperature, see Fig.2.

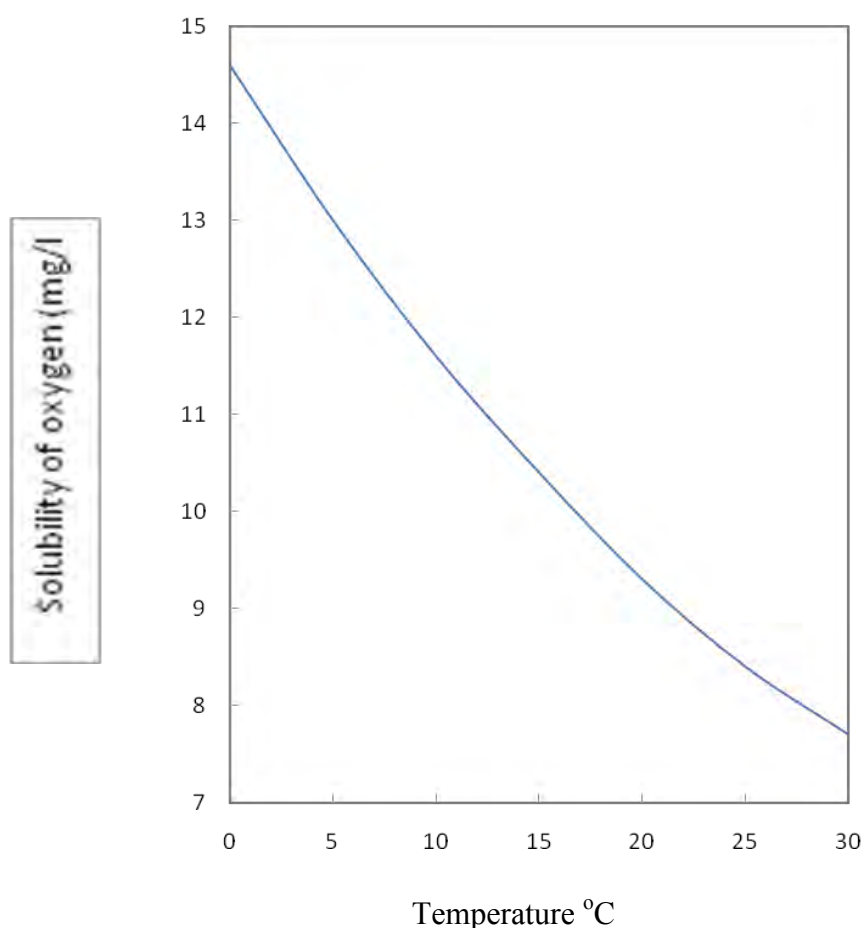


Fig.2 Saturation concentration of dissolved oxygen in fresh water

The rate of oxygen transfer (or rate of reaeration) depend om:

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- 1- The rate of absorption through the air-water interface.
- 2- The rate of dispersion within the body of water near the surface.

The driving force for oxygen transfer is the difference between the saturation concentration C_S of dissolved oxygen and the actual concentration C_L present in water. Since the solubility of oxygen in water is very low, the main resistance to mass transfer is on the liquid side of the interface so that the absorption is liquid-film controlled. The rate of oxygen transfer across unit area of surface in unit time, N , so that

$$N = k_L (C_S - C_L) \quad (1)$$

where

N = Oxygen transfer rate, $\text{kg/m}^2 \cdot \text{s}$

C_S = Saturation concentration of dissolved oxygen in water, mg/l

C_L = Actual concentration of dissolved oxygen in water, mg/l

k_L = Liquid phase mass transfer coefficient, m/s or m/day

If the oxygen is transferred into a volume of water, V , having a total interfacial area, A , in contact with the gas phase, then the rate of oxygen transfer per unit volume of water is given by

$$\frac{dC_L}{dt} = \frac{NA}{V} = K_L \frac{A}{V} (C_S - C_L) = r(C_S - C_L) \quad (2)$$

where

$\frac{dC_L}{dt}$ = is the oxygen transfer rate

$K_L \frac{A}{V}$ = reaeration or reoxygenation rate constant, $1/\text{day}$

$(C_S - C_L)$ = is the deference between the saturation concentration of DO and the actual concentration of DO presented in water. This deference is often referred as the oxygen deficit, D :

$$D = (C_S - C_L) \quad (3)$$

Photosynthesis

Photosynthesis requires solar energy radiation. During the process, the green plants such as algae (الطحالب) utilize carbon dioxide and the inorganic nutrient in the water to synthesis organic materials and liberate oxygen.

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Since the process occurs only during the presence of sun-light, the DO level in the water increases during the day.

Respiration

At night the algae and the micro-organisms compete with each other for both dissolved oxygen and organic compounds. This bacterial respiration is responsible for the production of carbon dioxide and subsequent depletion of dissolved oxygen.

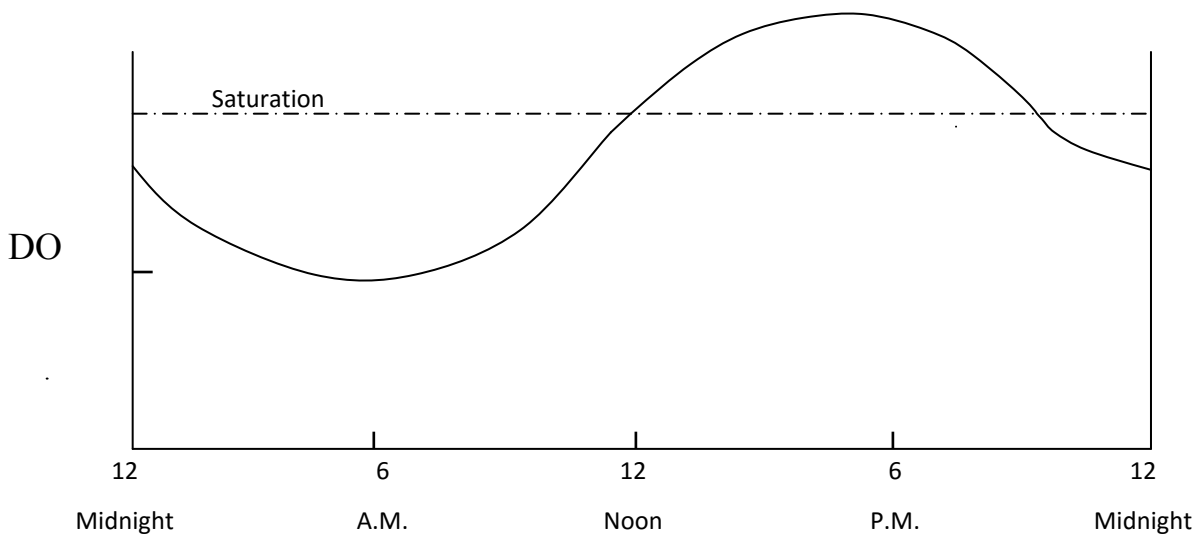


Fig.3 Diurnal variation of dissolved oxygen

Combination of the three effects of respiration, photosynthesis and reaeration results in a diurnal variation in dissolved oxygen concentration from the values that far exceed saturation during the day to much lower values or depletion at night (Fig.3).

Oxidation

In this process the oxygen is depleted by micro-organism during the oxidation of organic material

Pollution results when the oxygen demand exceeds the available oxygen

Biochemical Oxygen Demand, BOD

BOD is the measure of the oxygen utilized by micro-organism during the oxidation of organic material. BOD is the measurement for the water pollution.

If a given amount of organic matter is introduced, the rate of oxidation of organic matter (the rate of decline of BOD) can be approximated as a first-order chemical reaction whose may be expressed as:

$$\frac{dL}{dt} = -k_1 L \quad (4)$$

where

L = the BOD remaining in time t , mg/l

Integration of Eq,3 at time $t = 0$ and $L = L_u$:

$$\int_{L_u}^L \frac{dL}{L} = k_1 \int_t^0 dt$$

To get

$$\frac{L}{L_u} = \exp(-k_1 t) = 10^{-k_1' t} \quad (5)$$

$$k_1' = \frac{k_1}{2.303}$$

where

L_u = the ultimate BOD, mg/l

k_1 = the deoxygenation constant, 1/day.

The ultimate BOD means the original concentration of the organic material before any biological action has occurred.

The amount of BOD remaining at any time t , equals

$$L = L_u (10^{-k_1' t}) \quad (6)$$

If Y represent the amount of BOD utilized at any time t , then

$$L_u = L + Y \quad (7)$$

or

$$Y = L_u - L = L_u (1 - 10^{-k_1' t}) \quad (8)$$

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A standard way to measure the BOD is to determine the amount of oxygen required by bacteria during the first five days of decomposition at 20°C :

$$Y_5 = L_u - L_5 = L_u (1 - 10^{-5k_1'}) \quad (9)$$

Y_5 = the 5-day BOD at 20°C

The relationship among L , L_u and Y is shown in Figs 4 and 4. Fig.5 shows the BOD remaining versus time.

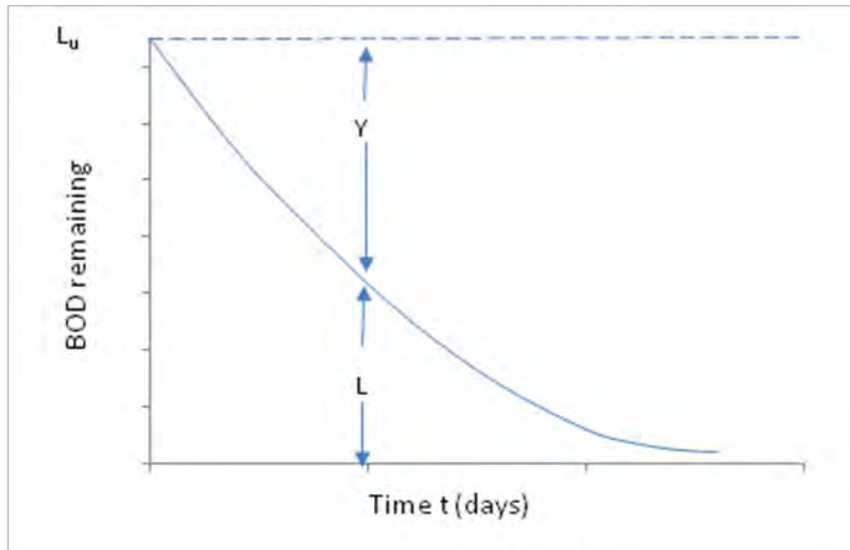


Fig.4 BOD remaining versus time

Fig.4 shows the BOD utilized versus time:

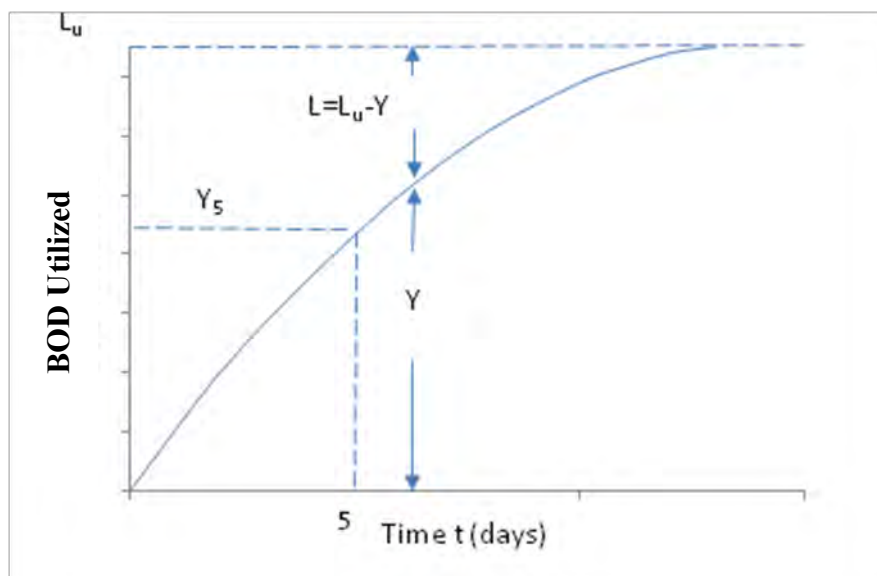


Fig.5 BOD utilized versus time

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Several methods are available for determining k_1' and L_u which include:

- (1) The least square methods. (2) The method of moments. (3) The daily difference method. (4) The rapid rate method. (5) The Thomas method.

The Thomas method is probably the simplest to use. This method is based on the similarity of two functions:

$$\frac{(1 - 10^{-k_1' t})}{2.3 k_1' t [1 + (2.3/6) k_1' t]^3} \quad (10)$$

Using this method the following equation can be written as:

$$\left(\frac{t}{Y}\right)^{1/3} = (2.3 k_1' L_u)^{-1/3} + \left[\frac{(k_1')^{2/3}}{3.43 (L_u)^{1/3}} \right] t \quad (11)$$

A plot of $(t/Y)^{1/3}$ versus time t will give a straight line whose slope, b and intercept a can be used to calculate k_1' and L_u

$$k_1' = 2.61 \frac{b}{a} \quad (12)$$

$$L_u = \frac{1}{2.3 k_1' a^3} \quad (13)$$

Table.2 show some typical values of k_1' and L_u .

Table.2. Some typical values of k_1' and L_u

Type of wastewater	k_1' (day ⁻¹)	L_u (mg/l)
Weak wastewater	0.152	150
Strong wastewater	0.165	200
Primary sewage effluent	0.152	75-150
Secondary sewage effluent	0.052-0.100	15-75

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Example 1

The following BOD results are observed for a sample of raw sewage at 20°C:

T (days)	0	1	2	3	4	5
Y (BOD, mg/l)	0	65	109	138	158	172

Calculate the reaction-rate constant k_1' and the ultimate BOD, L_u

Solution

1. Construct the following table for plotting,

$(t/Y)^{1/3}$	0.249	0.264	0.279	0.294	0.307
t	1	2	3	4	5

2. Plot the value $(t/Y)^{1/3}$ versus t (see the Fig.5 below)
3. From the plot: the slop b = 0.012, and the intercept a = 0.235
4. Computes k_1' and, L_u

$$k_1' = 2.61 \frac{b}{a} = k_1' = 2.61 \frac{0.012}{0.235} = 0.133 \text{ day}^{-1}$$

$$L_u = \frac{1}{2.3k_1'a^3} = L_u = \frac{1}{2.3(0.133)(0.235)^3} = 252 \text{ mg/l}$$

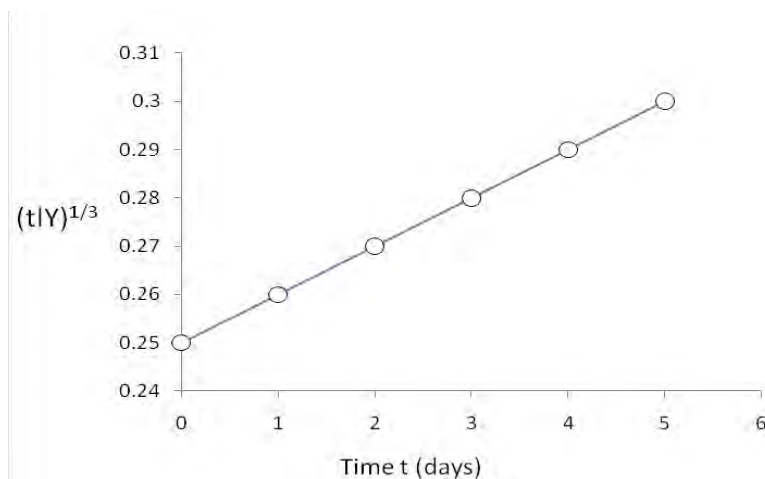


Fig.6 Example 1 $(t/Y)^{1/3}$ versus t

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The reaction rate constant k_1' depends on the temperature (T) and may be described by Van't Hoff Arrhenius equation:

$$\frac{d(\ln k_1')}{dT} = \frac{E}{R_u T^2} \quad (14)$$

where

E = activation energy, cal/mol

R_u = universal gas constant

T reaction temperature, K

Integration between the limits of T_o and T we get:

$$\ln \frac{k_{1,T}'}{k_{1,T_o}'} = \frac{E(T - T_o)}{R_u T T_o} \quad (15)$$

For most cases of the wastewater treatment processes the term $E/R_u T T_o$ is nearly constant, then Eq.15 becomes:

$$\ln \frac{k_{1,T}'}{k_{1,T_o}'} = \text{const.}(T - T_o) \quad (16)$$

Therefore

$$\frac{k_{1,T}'}{k_{1,T_o}'} = \exp[\text{const.}(T - T_o)] \quad (17)$$

Let $\exp(\text{const}) = \theta$ = temperature coefficient, then Eq.17 becomes:

$$k_{1,T}' = k_{1,T_o}' \theta^{(T - T_o)} \quad (18)$$

If the value of k_{1,T_o}' is determined at 20°C, then the reaction rate constant k_{1,T_1}' becomes

$$k_{1,T}' = k_{1,20}' \theta^{(T - 20)} \quad (19)$$

Note

Although θ was assumed to be constant. It varies slightly with temperature and the following values are recommended:

$\theta = 1.135$ for Temp. range 4-20 °C

$\theta = 1.056$ for Temp. range 20-30 °C

Example 2

Show that the ratio of the $2\frac{1}{4}$ -day, 35°C BOD to the 5-day 20°C BOD is approximately unity.

Solution

Putting $\Theta = 1.056$ in Eq.18, we get

$$k'_{1,35} = k'_{1,20}(1.056)^{(35-20)} = 2.264k'_{1,20}$$

Now

$$Y_5 = L_u \left(1 - 10^{-5k'_{1,20}} \right)$$

and

$$Y_{2\frac{1}{4}} = L_u \left(1 - 10^{-5(2.25)k'_{1,35}} \right)$$

or

$$Y_{2\frac{1}{4}} = L_u \left(1 - 10^{-5(2.25)(2.264)k'_{1,20}} \right)$$

$$Y_{2\frac{1}{4}} = L_u \left(1 - 10^{-5.09k'_{1,20}} \right) = Y_5$$

Oxygen sag curves

The discharge of waste into a body of water results in the depletion of dissolved oxygen level (deoxygenation) as the wastes oxidized by bacteria. Opposite to this drop in dissolved oxygen (depletion) is reaeration which replace oxygen through the surface of water, at a rate which is proportional to the rate of depletion of oxygen below the saturation value. The simulations action of oxygenation and reaeration produces a typical pattern in the dissolved oxygen concentration of aquatic system. This pattern is known as the dissolved-oxygen sag and the typical curve is shown in the Fig.7 below

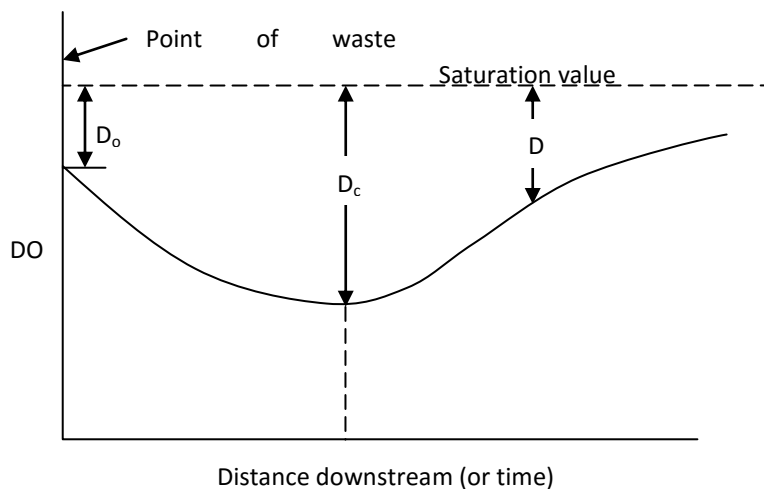


Fig.7 Oxygen sag curve

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The following conclusion can be seen from oxygen sag curve:

1. Initially the sag curve drops as the waste deplete the oxygen faster than it can be replaced.
2. At the point where the dissolved oxygen (DO) is a minimum, the rate of reaeration becomes equal to the rate of deoxygenation. This point is the critical point.
3. Beyond the critical point, the rate of reaeration exceeds the rate of deoxygenation and dissolved oxygen level (DO) begin to increase and eventually return to normal.

The simultaneous action of deoxygenation and reaeration can be described by the equation:

$$\frac{dD}{dt} = k_1 L - k_2 D \quad (20)$$

where

D = dissolved oxygen deficit, mg/l or kg/m³

L = concentration of organic material (the BOD remaining in time t), mg/l or kg/m³

k₁ = deoxygenation constant, day⁻¹

k₂ = reaeration constant, day⁻¹

L can be expressed in terms of ultimate BOD, L_u as (see Eq.4):

$$L = L_u e^{-k_1 t} \quad (21)$$

Substituting Eq.19 in Eq.18 and integrating we get:

$$D = \frac{k_1 L_u}{k_2 - k_1} (e^{-k_1 t} - e^{-k_2 t}) + D_o e^{-k_2 t} \quad (22)$$

where D is the dissolved oxygen deficit in time t, (mg/l) and D_o = initial oxygen deficit at the point of waste discharge (mg/l).

since
$$e^{-kt} = 10^{-k' t}$$

where
$$k' = \frac{k}{2.303}$$

then
$$D = \frac{k'_1 L_u}{k'_2 - k'_1} (10^{k'_1 t} - 10^{k'_2 t}) + D_o 10^{k'_2 t} \quad (23)$$

Both k'₁ and k'₂ are temperature dependent. The temperature effects on k'₁ as in Eq.17. The temperature effect on k'₂ can be evaluated as follows:

$$k'_{2,T} = k'_{2,20} (1.047)^{T-20} \quad (24)$$

where

$k'_{2,T}$ = reaeration constant at temperature T °C

$k'_{2,20}$ = reaeration constant at temperature 20 °C

The critical dissolved oxygen deficit D_c , where the rate of oxygen utilized for waste material decomposition equals to the rate of atmosphere reaeration, and this can be evaluated by simply setting $dD/dt = 0$ in Eq.18 and $D = D_o$, as:

$$k_1 L - k_2 D_c = 0$$

$$L = L_u e^{-k_1 t}$$

and

then
$$k_2 D_c = k_1 L = k_1 L_u \exp(-k_1 t_c)$$

$$D_c = \frac{k_1}{k_2} L_u \exp(-k_1 t_c) \quad (25)$$

the critical time (t_c) can be obtained by differentiating Eq.20 with respect to t_c can be obtained by differentiating Eq.20 with respect to t and setting dD/dt to get:

$$t_c = \frac{1}{k_2 - k_1} \ln \left[\frac{k_2}{k_1} \left(1 - D_o \frac{k_2 - k_1}{k_1 L_u} \right) \right] \quad (26)$$

k'_1 can be evaluated from the BOD test in the laboratory

k'_2 must be determined from field information . O'Conner and Dobbins gave the following empirical equation for determining k'_2 at 20 °C

$$k_2 = 3.9 \frac{V^{0.5}}{H^{1.5}} \quad (27)$$

where

V = velocity of flow, m/s

H = depth of flow, m

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conditions required to reach the critical point is significant because at this point reaches zero, then anaerobic conditions may prevail leading to the death of aerobic inhabitants. This is illustrated in Fig. 7.8 for three different levels of BOD discharge from a point source.

Example 3

The town of Venkatapur discharges 17,360 m³/d of sewage into a nearby stream. The stream has a minimum flow of 0.4 m³/s, depth of 2.5 m and a velocity of 5 kmph. Other information pertaining to the stream and the sewage are as follows:

	Temp (°C)	DO (mg/l)	BOD ₅ (mg/l)
Stream	20	8.5	10
Sewage	25	1.0	200

The deoxygenation constant (k_1) evaluated at 20°C = 0.35 d⁻¹. Determine the critical oxygen deficit, D_c , and its location, x_c .

Solution

The flow of sewage into the stream,

$$Q_{se} = \frac{17360 \text{ m}^3/\text{d}}{(86400 \text{ s/d})} = 0.20 \text{ m}^3/\text{s}$$

The temperature of the stream after mixing,

$$T_m = \frac{Q_{se}T_{se} + Q_{st}T_{st}}{Q_{se} + Q_{st}}$$

Substituting the values,

$$T_m = \frac{0.2(25) + 0.4(20)}{0.2 + 0.4} = 21.7^\circ\text{C}$$

Similarly, the DO of the stream after mixing,

$$DO_m = \frac{Q_{se}DO_{se} + Q_{st}DO_{st}}{Q_{se} + Q_{st}}$$

Substituting the values,

$$DO_m = \frac{0.2(1.0) + 0.4(8.5)}{0.2 + 0.4} = 6.0 \text{ mg/l}$$

The BOD₅ = Y_5 , after mixing is similarly given by

$$Y_{5,m} = \frac{Q_{se}Y_{5,se} + Q_{st}Y_{5,st}}{Q_{se} + Q_{st}}$$

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Substituting the values,

$$Y_{5,m} = \frac{0.2(200) + 0.4(10)}{0.2 + 0.4} = 73.3 \text{ mg/l}$$

The ultimate BOD after mixing is then calculated:

$$L_{u,m} = \frac{Y_{5,m}}{1 - e^{-5k_1}}$$

In the above equation k_1 , is evaluated at 21.7°C , the temperature of the stream after mixing the sewage.

We have, from data $k_{1,20} = 0.35 \text{ d}^{-1}$

Now $k_{1,21.7} = k_{1,20} \theta^{(21.7-20)}$

Taking $\theta = 1.056$

$$k_{1,21.7} = 0.35(1.056)^{(21.7-20)} = 0.384 \text{ d}^{-1}$$

Therefore,

$$L_{u,m} = \frac{73.3}{1 - e^{-5(0.384)}} = 86.2 \text{ mg/l}$$

The saturation concentration of dissolved oxygen at $21.7^\circ\text{C} = 9.0 \text{ mg/l}$ (from Fig. 7.1)
Therefore, the initial oxygen deficit,

$$D_0 = 9.0 - 6.0 = 3.0 \text{ mg/l}$$

The reaeration constant, k_2 , at 20°C can be calculated using Eq. (7.31):

The velocity of the stream = 5.0 kmph

or $V = 1.39 \text{ m/s}$. The depth of the stream, $H = 2.5 \text{ m}$. Substituting these values in Eq. (7.31):

$$k_{2,20} = \frac{3.9(1.39)^{0.5}}{(2.5)^{1.5}} = 1.16 \text{ d}^{-1}$$

The reaeration constant, k_2 , at 21.7°C can be obtained from Eq. (7.28):

$$k_{2,21.7} = 1.16(1.047)^{(21.7-20)} = 1.25 \text{ d}^{-1}$$

The critical time using Eq. (7.30):

$$t_c = \frac{1}{(1.25 - 0.384)} \ln \left[\frac{1.25}{0.384} \left(1 - 3.0 \frac{(1.25 - 0.384)}{0.384(86.2)} \right) \right]$$

$$t_c = 1.264 \text{ d}$$

The critical distance, $x_c = t_c V = (1.264) (5) (24) = 152 \text{ km}$

7.3.2 Disease Causing Agents

Water is a potential carrier of pathogenic micro-organisms. These pathogens are carried

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Wastewater treatment

The objective of wastewater treatment is to reduce the concentration of pollutants in water to the level so that the treated water will meet the acceptable quality standards and will not adversely affect the environment.

Wastewater

Wastewater can be defined as any water that contains impurities or pollutants in the form of solid, liquid or gases or their combinations in such a concentration that is harmful if disposed into the environment.

Classification of wastewater

Wastewater can be classified by their origin as: domestic wastewater and industrial wastewater.

1. **Domestic wastewater:** that is collected and discharged from residential and commercial establishments.
2. **Industrial wastewater:** is formed at industrial plants where water is used for various processes and also for washing and rinsing of equipment.

Wastewater treatment

The wastewater treatment processes are usually grouped as

1. Primary treatment: this process removes identifiable floating and suspended solids. Primary treatment system is always physical process.
2. Secondary treatment: this is designed to remove the organic matter that is soluble or in the colloidal form. These processes are commonly biological in nature.
3. Tertiary treatment or advanced treatment: this treatment may involve physical, chemical or biological processes or their various combinations depending on the impurities to be removed. The advanced waste treatment processes are expensive, and are used only when water produced is required to be of high quality.

1. Primary treatment

Primary treatment is mainly a removal of floating and suspended solids through the following steps:

a. Pretreatment:

Wastewater is pretreated to remove large floating and suspended solids. It consists of:

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1. Screening: Screens of various sizes and shapes are used depending on the nature of solids to be removed. Fixed bar screens are the most common types of screen used in domestic wastewater facilities.
2. Grit removal: After screening the wastewater enters the grit chamber for removal of inorganic grit consisting of sand and gravels without removing the organic material.

b. Sedimentation:

In this step, the settleable solids are removed by gravitational settling. Settling tank is used to settle as much of the solids matter as possible. . The settling tank which follows pretreatment is known as a primary clarifier. The solids settle at the bottom of the tank as a raw sludge. This sludge is removed as underflow either by vacuum or by raking it to a discharge point at the bottom of the tank, while the clarified liquid escapes as overflow. Sedimentation tank may be rectangular or circular tank.

c. Flocculent settling:

The process of flocculent settling take places when the velocity of the particles increases due to coalescence with other particles.

d. Flotation:

Flotation may be used in place of sedimentation for treating industrial wastewater containing finely divided suspended solids and oily matter.

2. Secondary biological treatment:

The water leaving the primary treatment has lost the sold matter but still contains the organic matter. This organic matter still represents a high demand for oxygen, BOD. This demand for oxygen must be removed. The objective of secondary treatment is thus to remove BOD. The following systems used for secondary biological treatment:

a. Activated sludge system:

Wastewater after primary treatment enters an aeration tank where the organic is brought into intimate contact with the sludge from the secondary clarifier. This sludge is heavily laden with microorganisms which are in active state of growth. Air is introduced into the tank, either in the form of bubbles through diffuser or by surface aerators. The microorganisms utilized the oxygen in the air and convert the organic matter into stabilized compounds such as NO_3 , SO_4 , CO_2 , and synthesis new bacteria cells. The effluent from the aeration tank containing the flocculent microbial mass known as the sludge, is separated in settling tank which called a secondary or final clarifier. In the

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settling tank the separated sludge exists without contact with organic and becomes activated. A portion of the activated sludge is recycled to the aeration tank as seed and the rest is wasted, as shown in Fig.8. The activated sludge system consists of:

- 1- Aeration tank.
- 2- Solid-liquid separator.
- 3- Recycle activated sludge.

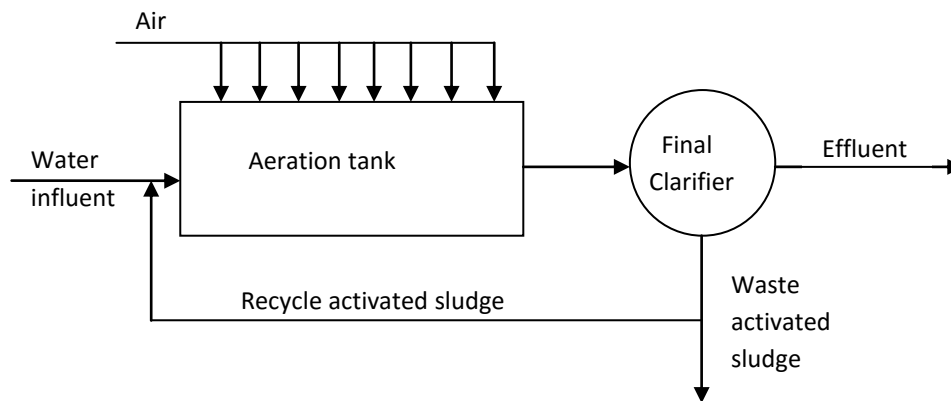


Fig.8. Block diagram of the activated sludge system

b. Trickling-filter(biological-film system):

Wastewater is brought into contact with a mixed microbial population in the form of a slim film attach to the surface of a solid support medium (rocks). Trickling filters are most popular for treating domestic sewage because of its ease of operation.

c. Sludge treatment and disposal:

Handling and disposal of sludge from secondary biological wastewater treatment plants is an important problem. The common unit operation of sludge treatment and disposal are concentration or thickening, digestion, conditioning, dewatering, oxidation, and safe disposal.

3. Tertiary treatment(Advanced treatment):

The effluent from a typical secondary treatment still contains a significant amount of various types of pollutants such as suspended solids, BOD, nutrient, dissolved solids, and toxic substances. A variety of methods are used to satisfy any of several specific goals which are:

- 1- Removal of suspended solids.
- 2- Removal of BOD.
- 3- Removal of nutrient.

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- 4- Removal of dissolved solids
- 5- Chemical oxidation.

1. Removal of suspended solids (SS)

Several methods are used to remove of suspended solids, but the most commonly methods used are:

- 1-Microscreening
- 2- coagulation.

2. Removal of BOD

There are four main types

- 1- Aerobic ponds.
- 2- Facultative ponds.
- 3- Aerated ponds
- 4- Anaerobic ponds.

3. Removal of nutrient

Include removal of nitrogen and phosphorous as described below:

3.1.Nitrogen removal:

All forms of nitrogen in wastewater effluent are harmful. Two popular methods of nitrogen removal are:

- 1- *Ammonia stripping*: after second treatment all the nitrogen exit as ammonia. This can be removed by stripping.

- 2- *Nitrification- denitrification*:

Nitrification is the process in which bacteria convert ammonia nitrogen to nitrate ions, NO_3^- .

De-nitrification is the process of reduction of the nitrate ions, produced from nitrification process, by anaerobic bacteria.

3.2.Phosphorous removal:

The main processes used for the removal of phosphorous from wastewater are:

- 1- Chemical precipitation,
- 2- Biological phosphorous removal.

4. Removal of dissolved solids

The dissolved solids are both organic and inorganic types. Number methods have been used for the removal:

- 1- Adsorption by activated carbon.
- 2- Solvent extraction.
- 3- Ion exchange.

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- 4- Reverse osmosis.
- 5- Electrodialysis.

5. Chemical oxidation

Chemical oxidation are widely used for disinfection, removing organic materials that are resistant to biological or other treatment processes and conversion of cyanides to innocuous products. This process can be done by:

- 1- Chlorine.
- 2- Ozone.

Example:

In order to facilitate the above three steps of wastewater treatment, primary, secondary, and advanced, a typical wastewater (Table.3) will be assumed. It will be further assumed that the effluent from this wastewater treatment must following effluent standard:

$$\begin{aligned} \text{BOD} &\leq 15 \text{ mg/l} \\ \text{SS} &\leq 15 \text{ mg/l} \\ \text{P} &\leq 1 \text{ mg/l} \end{aligned}$$

Table.3. Characteristic of a typical domestic wastewater

Parameter	Typical Value for domestic sewage, Mg/l
Biochemical oxygen demand, BOD	250
Suspended solids, SS	220
Phosphorous	8

After the primary, secondary, and tertiary treatment the approximate water quality obtained and presented in Table.4.

Table.4. Characteristic of a typical domestic wastewater after primary, secondary, and tertiary treatment

Parameter	Raw wastewater	Following primary treatment	Following secondary treatment	Following tertiary treatment
BOD	250	175	15	10
SS	220	60	15	10
P	8	7	6	0.5

It can be said that: Primary treatment is mainly to remove of solids, although some BOD is removed. Secondary treatment is to remove part of BOD and the remaining suspended solids, SS.

Tertiary treatment is more efficient in the removal of BOD and SS.

Air pollution

Air pollution may be defined as any atmospheric condition in which certain substances are present in such concentration that can produce undesirable effects on man and his environment. These substance include gases, particulate, radioactive materials, and many others. Most of these materials are naturally present in the atmosphere in low concentrations and are usually considered to be harmless.

Classification of air pollutants

The air pollutants may be classified in different ways as follows:

1) According to origin:

A. Primary pollutants are those that are emitted directly from the sources into the atmosphere. A general list of primary air pollutants are:

- 1- Particulate matter such as ash, smoke, dust, fumes, mist, fog, spray, and aerosol.
- 2- Inorganic gases such as sulfur dioxide, hydrogen sulfide, nitric acid, ammonia, carbon monoxide, carbon dioxide, and hydrogen fluoride.
- 3- Olefin and aromatic hydrocarbons.
- 4- Radioactive compound.

Carbon dioxide is generally not considered an air pollutant but, because of its global concentration, its influence on global climate is a great concern.

B. **Secondary pollutants** are those that are formed from chemical and photochemical interactions among primary pollutants and normal atmospheric constituents in the atmosphere. Pollutants such as sulfur trioxide, nitrogen dioxide, PAN (peroxyacetyl nitrate), ozone, aldehydes, ketenes and various sulfate and nitrate salts.

2) According to state of matter:

- A. Gaseous pollutants which get mixed with air and do not normally settle e.g. CO, NO_x, and SO₂.
- B. Particulates pollutants which comprised of finely divided solids or liquids and often exist in colloidal state as ash, smoke, dust, fumes, mist, fog, spray, and aerosol.

Sources of air pollution

Air pollution results from gaseous emissions from:

- (a) **Industrial waste:** There are numbers of industries which are sources of air pollution. Petroleum refinery are the major source of gaseous pollutants, Cement

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factories emit plenty of dust, stone crushers, food and fertilizers industries which emit gaseous pollutants, and chemical manufacturing industries which emit acid vapors in air.

(b) Thermal power stations: The chief pollutants are fly ash, SO_2 , and other gases and hydrocarbons.

(c) Automobiles: the source of emission of vehicles exhaust. This exhaust produced many air pollutants such as CO, NO_x lead oxides

Air Pollutants emission from petroleum refinery and their effects

The petroleum refining process results in the release of a number of air pollutants, including:

- Sulfur Oxides SO_x
- Nitrous oxides NO_x
- Carbon Monoxide CO
- Volatile Organic Compounds (VOC)
- Particulate matter
- Greenhouse gases (GHGs)

Sulfur oxides SO_x

Sulfur dioxide SO_2 , belongs to the family of sulfur oxides gases (SO_x). It is formed from the sulfur containing in raw materials such as coal, oil and metals – containing ores during combustion and refining processes.

SO_2 dissolves in water vapor in the air to form acids, and interacts with other gases and particles in the air to form particles known as sulfates and other products that can be harmful to people and their environment.

Nitrogen oxides NO_x

Nitrogen oxides NO_x include the gases: Nitrogen oxide NO and Nitrogen dioxide NO_2 .

NO_x formed primarily from the liberation of nitrogen contained in fuel and nitrogen contained in combustion air during combustion processes.

NO emitted during combustion quickly oxidized to NO_2 in the atmosphere.

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NO₂ dissolved in water vapor in air to form acids, and interacts with other gases and particles in the air to form particles known as nitrates and other products that may be harmful to people and their environment.

Particulate matter (PM)

Particulate matter (PM) consists of air born particles in solid or liquid form. They can be suspended droplets or solid particles or mixture of the two.

PM may be classified as primary or secondary, depending on the compounds and processes involved during its formation:

- Primary PM is emitted at the emissions source in particle form, for example, the smokestack of an electrical power plant or a recently tilled field subject to wind erosion.
- Secondary PM Formation results from a series of chemical and physical reactions involving different precursor gases, such as sulfur oxides and nitrogen oxides, and ammonia reacting to form sulfate, nitrate and ammonium particulate matter.

Particulates can be composed of inert or extremely reactive materials ranging in size from 100 µm down to 0.1 µm and less. The inert materials do not make any changes in the environment as a result of combustion or any other process, whereas the reactive materials could be further oxidized or may react chemically with the environment.

Air borne particulate

Air born particles can be classified as:

Dust: Solid particles of size ranging from 1 to 200 µm. These are formed by natural disintegration of rock and soil or by the mechanical process of grinding and spraying.

Smoke: Fine particles of size ranging from 0.01 to 1 µm, which are they liquid or solid, and are formed by combustion.

Fume: Solid particles of the size ranging from 0.1 to 1 µm, and are normally released from chemical or metallurgical processes.

Mist: Liquid droplets generally smaller than 10 µm, which are formed by condensation in the atmosphere or released from industrial operations.

Fog: It is the mist in which the liquid is water.

Aerosol: These included all air-born suspensions either solid or liquid. These are generally smaller than 1 µm.

Atmosphere of Earth and Global Problem

Atmosphere of earth

The atmosphere comprises of a mixture of gases surrounding the planet earth. It acts as a gaseous blanket protecting the earth by absorption the dangerous ultraviolet solar radiation (UV), warming the surface of the earth through the heat retention (greenhouse effect). The 'greenhouse effect' which keeps the earth warm enough to sustain the life on the earth. It extends up to about 500 km above the surface of the earth.

Composition of Earth's atmosphere

Normal composition of clean, dry air at or near the sea is as following:

- The major gases of the atmosphere are: N_2 , O_2 , and Water vapor (H_2O).
- The minor gases in the atmosphere are: Argon (Ar) and carbon dioxide (CO_2).
- The trace gases in the atmosphere are: Methane, Nitrous oxide, Hydrogen, ozone, Nitrogen dioxide, Carbon monoxide, Ammonia, Neon, Helium, etc.

Layers of Earth's atmosphere:

The atmosphere which extended up to about 500 km above the earth's surface can be broadly divided into four major regions with widely varying temperature even within each region. These regions are:

1. Troposphere

This layer is closest to the Earth's surface, and extends up to an altitude of 11 km. It is also the layer where majority of our weather occurs. This layer is primarily composed of 78% nitrogen and 20.9% oxygen (make up air) and other gases including greenhouse gases. All atmospheric water vapor or moisture is found in this layer.

2. Stratosphere:

This layer lies directly above the troposphere. It extends about 11-50 km above the Earth's surface. It contains the ozone layer. About 90% of the ozone in the Earth's atmosphere is found in this region. The ozone layer absorbs the ultraviolet radiation from the Sun. very little weather occurs in the stratosphere.

3. Mesosphere:

This area is directly above the stratosphere, it extends about 50-85 km above the Earth's surface.

4. Thermosphere:

This layer extends from 85-500 km above the Earth's surface.

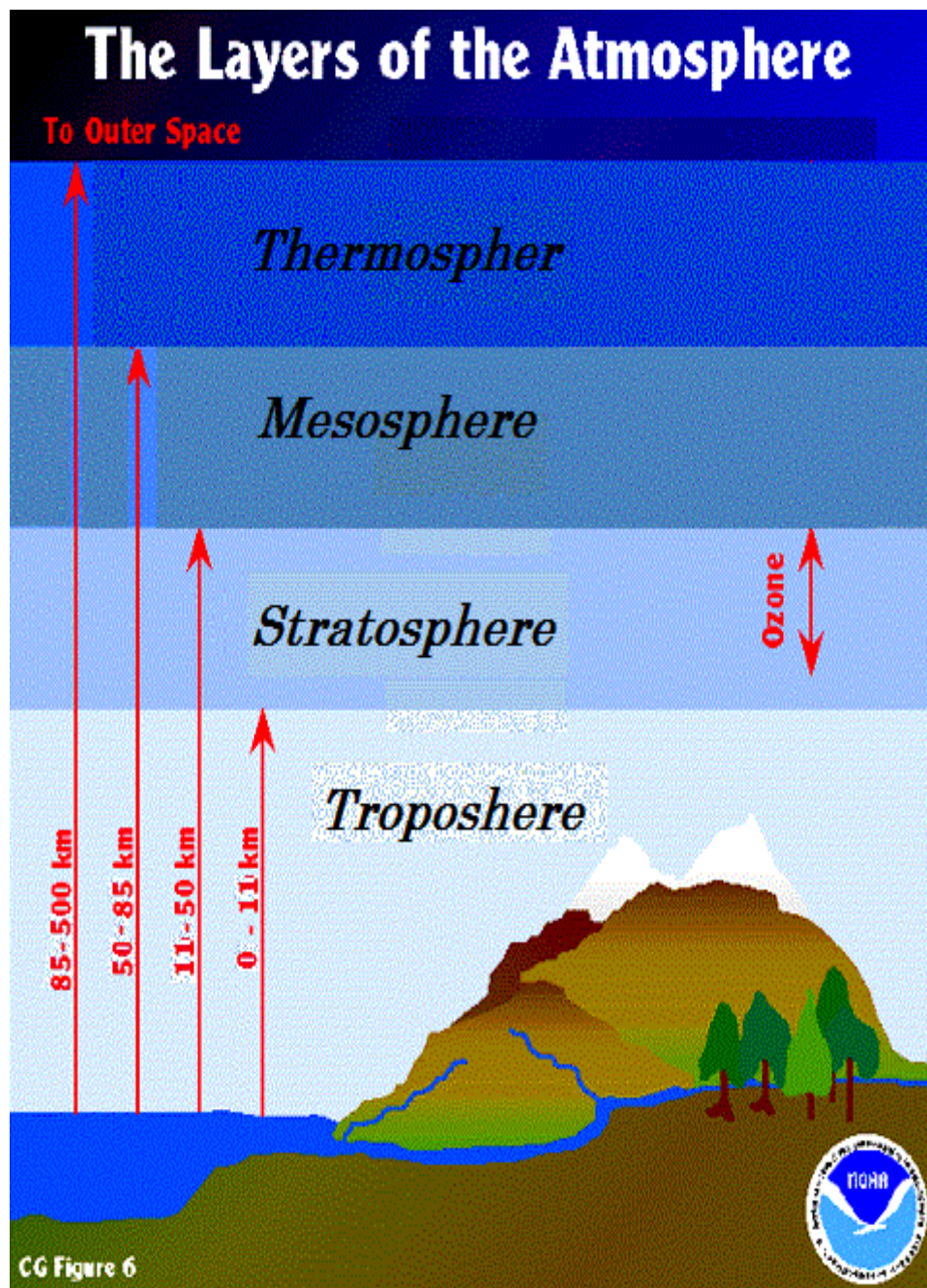


Fig.9 Layers of air atmosphere

Global air pollution problems

The main global pollution problems are:

1. Greenhouse effect and global warming,
2. Ozone depletion,
3. Acid rain.

1) Greenhouse Effect and global warming

Greenhouse Effect:

The solar energy coming from the sun passes through the atmosphere gases to reach the Earth's surface. Roughly one-third of this radiation absorbed is reflected directly back to the space. The remaining two-thirds are absorbed by the earth's surface and warm it. A long wave infrared (IR) radiation (heat) emitted from the Earth's surface. Some of IR radiation passes through the atmosphere into the space and some of it is absorbed by certain gases in the atmosphere, called greenhouse gases and re-emitted in all direction. The effect of this is to warm the Earth's surface and the lower atmosphere. This phenomenon is called the greenhouse effect. These gases essentially act as blanket, making the earth's surface warmer than otherwise it would be.

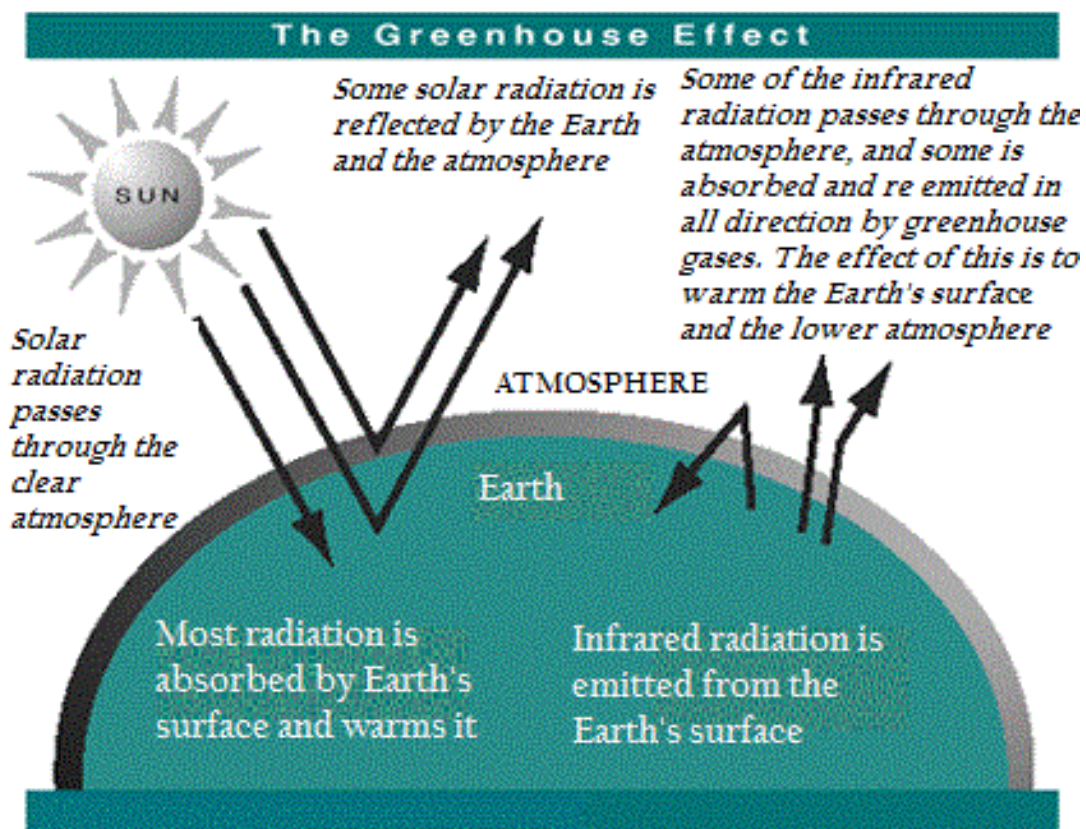


Fig.10 The Greenhouse effects

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Major greenhouse gases are

Greenhouse Gas	Chemical symbol	Sources
Water vapor	H ₂ O	Naturally occurring. Rising global temperatures may act to increase water vapor in the atmosphere.
Carbon Dioxide	CO ₂	Naturally occurring. Also it occurs as a result of human activities such as burning of coal, oil, and natural gases.
Methane	CH ₄	It produces by both the natural and human process. It is produced when plants decay and where there is very little air. It is also called swamp gas because it is abundant around the water and swamps.
Nitrous Oxide	N ₂ O	Generated by burning fossil fuels, in the manufacture of nitrogen fertilizer and by use of this fertilizers in agricultural.
Ozone	O ₃	Naturally occurring. Ultraviolet radiation and oxygen interacted to form ozone in atmosphere. Ozone layer helps to protect the earth from ultra-violet radiation
Chlorofluorocarbons, CFCs	Various compounds	Increasing the use of CFCs tend to destroy ozone in the upper atmosphere causing depletion the ozone layer.

Among the greenhouse gases, water vapor and carbon dioxide are the most important greenhouse gases.

The greenhouse gases acting like the greenhouse allow the solar radiation in the range 300 to 2500 nm (e.g. near UV, visible and near IR region), while filtering the dangerous UV radiations (e.g. < 300 nm)

Important of greenhouse effect:

The important of greenhouse effect is:

1. To maintain the average temperature of world. The average temperature should remain constant and governs all life process.
2. To maintain the sea level.
3. The polar ice caps remain intact.

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Global warming

Global warming is increase in global average temperature near the Earth's surface as a result of increasing in concentration of greenhouse gases in the atmosphere from human activities. If more greenhouse gases are added to the atmosphere from human activities, they will absorb more of infrared radiation reflected by the Earth's surface. The surface and the lower atmosphere will warm further. This extra warming is called the enhanced greenhouse effect. Enhanced greenhouse effect causes global warming.

Since the beginning of industrialization, 200 years ago, concentration of these gases has increases. It is estimated that the Earth's average temperature has raised 0.6 °C since 1880 because of emission of greenhouse gases from human activities.

Effects of global warming

The following effects will results from the global warming (rising temperature):

- 1- Thermal expansion of the water and melting of polar ice caps would cause sea level to rise.
- 2- Could lead to changes in regional wind systems which would influence global rainfall distribution and lead to redistribution and frequently of flood, drought, and forest fires.
- 3- growth in insect population: Climate change would create favorable conditions for growth in insect population, which this have bad effect on agriculture and human health.
- 4- Disrupts the Water supply and droughts would be more common.

International action to reduce global warming

Kyoto protocol : Held in December 1997, at the city of Kyoto. The Kyoto is a legally binding agreement under which 37 developing countries committed themselves to reduce their annual greenhouse gases emission to an average of 5% less than 1990 levels by 2012 because they are responsible for 36% of the world CO₂ emission. Now more than 500 cities around the world have taken up programs to reduce their greenhouse emission.

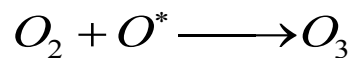
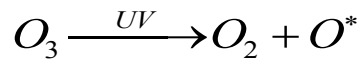
Controlling global warming

- 1- Reduce deforestation and develop way to sustainable agriculture.
- 2- Use of technologies to absorb CO₂ from emission.
- 3- Increased absorption of CO₂ by planting more trees.
- 4- Sequester CO₂ in deep ocean.
- 5- Increased dependence on renewable energy source.

2) The Ozone Layer and Ozone Layer Depletion

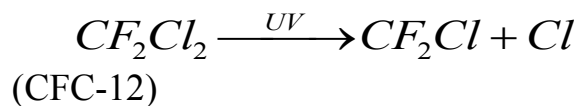
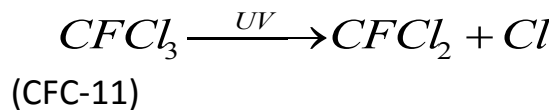
The Ozone Layer

The ozone layer in the stratosphere serves as a shield, protecting the earth's surface from the sun's ultraviolet radiation (UV). Ozone layer absorbs 97-99% of the UV radiation. As the ozone absorbs UV-radiation, it is broken into oxygen molecule and oxygen radical. The oxygen and the oxygen radical then recombine to form new ozone molecule, available to absorb more UV-radiation.

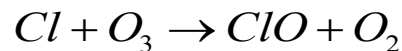


Ozone layer depletion

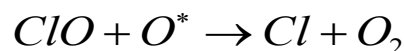
The ozone layer depletion occurs as results of releasing of chemicals such as chlorofluorocarbons (CFCs). CFCs when first used in air conditioning and refrigeration systems valued for their non-toxic and stable properties. CFCs introduced in the lower troposphere pass through the ozone without any change and reach the stratosphere. Here, they impact by the UV-radiation and release destructive chlorine atoms:



The chlorine atom quickly reacts with the ozone molecule breaking it into oxygen:



The ClO produced reacts with oxygen radical forming more chlorine atom that can react with more ozone



The above reaction also removes the oxygen radical thus preventing it from recombined with the oxygen to form an ozone molecule. The overall effect is a decrease in the amount of ozone that leads to ozone removal from stratosphere.

Source of ozone layer depletion

The facts the ozone layer depletion was discovered in the mid of 1980. The main source of ozone layer depletion is

- 1- Chlorofluorocarbon, CFCs: CFCs are cause damage to ozone layer. When CFCs reach the upper atmosphere they are degraded by UV radiation to produce chlorine atom. This atom breaks up ozone molecules to form oxygen and ozone then disappear and depleted.
- 2- Nitrous oxide: It produces from the microbial action on the nitrogenous fertilizers, which cause depletion of the ozone layer.
- 3- Nuclear test: Nuclear explosions release high quantity of various gases and other materials which damage the ozone layer.

International action to protect the ozone layer

Montreal protocol: is an international agreement signed in Montreal city of Canada in 1987. Its goal was to cut emission of CFCs into atmospheres by about 35% between 1989 and 2000.

3) Acid rain

Acid rain is mainly caused by the release of sulfur dioxide (SO₂) and oxide of nitrogen (NO_x) during fossil fuel combustion and the use sulfur coal and oil. When these gases are discharged into atmosphere they react with water, oxygen, and other gases in the atmosphere to form sulfuric acid, ammonium, and nitric acid. These acids then disperse over large areas because of wind patterns and fall back to the ground with rainwater as acid rain.

Unpolluted rain is naturally acidic with a pH of about 5.6 due to CO₂ in the atmosphere, which reacts with rainwater forming carbonic acid (H₂CO₃):



Carbonic acid is a weak acid and the acidity in rainwater can quickly be neutralized on contact with materials. But the presence of sulfuric acid or nitric acid in the atmosphere

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could lower the pH of rain droplets to value below 5.6 and such rain is considered acidic and it called "acid rain".

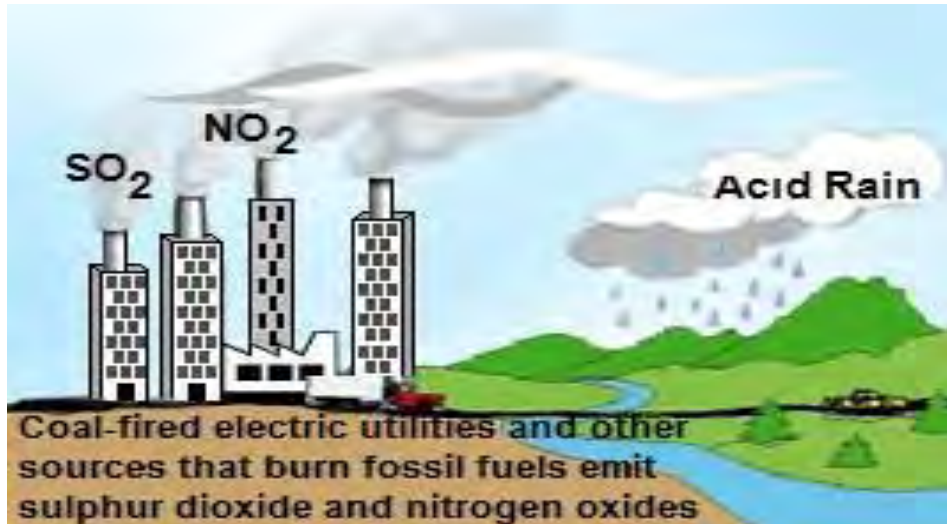


Fig.11 The acid rain

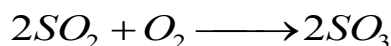
Effects of acid rain

The harmful effects caused by acid deposition can be categories under many effects:

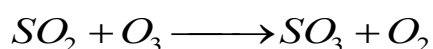
- 1- Effects on water bodies: acid rain causes acidulation of lake and streams and contributes to damage of tree at high elevation and much sensitive forest.
- 2- Effect on material: acid rain accelerates the decay of building, bridge, and other structures may by corrosion.
- 3- Effect of human health: acid rain caused acidification of air, water and food that damage the human health. It can also release heavy metals from the pipes of the distribution systems into the potable water supply.

Chemical processes of acid formation in atmosphere

A large part of SO_2 in the atmosphere is oxidized to sulfur trioxide SO_3 :

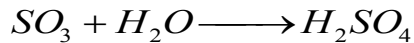


Also SO_2 reacted with atmospheric ozone to give sulfur trioxide SO_3 :

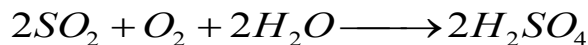


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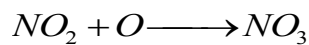
Sulfur trioxide SO_3 is then quickly combined with moisture (water) in the atmosphere to form sulfuric acid mist:



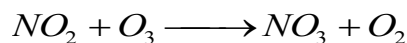
The overall reaction is:



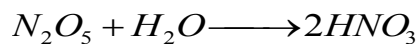
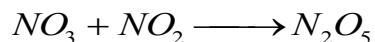
Nitrogen dioxide reacts with atomic oxygen to give nitrogen trioxide:



Also NO_2 reacted with atmospheric ozone to give nitrogen trioxide NO_3 :



NO_3 reacted with NO_2 forming N_2O_5 , which react with moisture (water) forms nitric acid:



Control strategies for acid rain

- 1- The use of low sulfur coal or substitution of coal by other fuels.
- 2- Alternative methods for power generation instead of thermal power plants, such as hydropower facilities or nuclear power.
- 3- Installation of flue gas desulfurization systems in large power plants can reduce emission of SO_2 .

Meteorological Aspects of Air Pollutant Dispersion

Lapse rate

The decrease in temperature with increase in altitude while moving upward through the earth's atmosphere. This represents by

$$\frac{dT}{dz}$$

Type of lapse rate

There are two types of lapse rate:

- Environmental lapse rate (ELR): This refers to the actual reduction of temperature with altitude in the stationary atmosphere (non-rising air). It averages about 6.5 °C per kilometer in the lower atmosphere (troposphere).
- Adiabatic lapse rates (ALR): these refer to the change in temperature of a parcel of air as it moves vertically upwards (or downwards) without exchanging heat with its surrounding. There are two adiabatic
 - DALR: Dry adiabatic lapse rate (dry air cool at 10 °C / km)
 - WALR: Saturated (or Moist) Adiabatic lapse rate (moist air cool at 6 °C / km)
(it means the air parcel saturated with water vapor)

Adiabatic lapse rate (ALR)

The adiabatic decrease in temperature with altitude is especially important in vertical movement of air pollutants and can be explained by utilizing the concept of an air parcel, which is pictured as a little sphere of air. As the air parcel rises in the atmosphere, it goes through the region of decreasing pressure and expands to accommodate the decreasing pressure. As it expands, it does work on the surroundings, since the process is usually rapid; there is no heat transfer between the air parcel and the surrounding air.

Hence, for the case of adiabatic process the first law of thermodynamics yields,

$$-dW = dU \quad (1)$$

Where

dU : is change in the internal energy of the system (parcel), J

dW : is the work done by the system in the surroundings, J

The negative sign, means that the internal energy decreases thereby decreasing the temperature.

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Now the work done by the system on the surroundings (dW),

$$dW = p dV$$

And the change in internal energy becomes,

$$dU = C_v dT$$

where

C_v : is the specific heat at constant volume per unit mass of parcel, J/kg.K (kg air parcel).

Substituting dW and dU in Eq. (1), we get

$$p dV + C_v dT = 0 \quad (2)$$

Eq. (2) may be written for unit mass of the air parcel as,

$$p dv + C_v dT = 0 \quad (3)$$

where :

P : pressure, N/m², or atm

T : temperature, °C, or K

v : is the specific volume, m³/kg

The perfect gas equation:

$$pV = nRT \quad (4)$$

Eqn (4) in term of specific volume v :

$$p v = RT \quad (5)$$

Differentiating Eq. (5) in term of P and v

$$p dv + v dp = R dT \quad (6)$$

Sub Eq. (6) in Eq. (3) and rearrange to give:

$$(C_v + R) dT = v dp \quad (7)$$

The variation of the temperature with altitude can be written as a product of two terms:

$$\frac{dT}{dz} = \frac{dT}{dp} \frac{dp}{dz} \quad (8)$$

where z is the altitude

Rearranging Eq. (7), we obtain:

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$$\frac{dT}{dp} = \frac{\nu}{C_v + R} \quad (9)$$

The change in the pressure with altitude (z) in vertical direction can be represented by the relation:

$$\frac{dp}{dz} = -\rho g \quad (10)$$

The atmospheric density can be expressed using perfect gas relation:

$$p = \rho RT \quad (11)$$

Then the variation of pressure with altitude can be obtained by substituting of Eq. (11) into (10):

$$\frac{dp}{dz} = -\frac{pg}{RT} \quad (12)$$

And the specific volume ν :

$$\nu = \frac{1}{\rho} \quad (13)$$

Substituting Eq. (9), (12) and (13) into Eq. (8), we get:

$$\frac{dT}{dz} = -\frac{g}{C_v + R} \quad (14)$$

Noting that $C_v + R = C_p$, where C_p the specific heat at constant pressure per unit mass of the parcel, we can write Eq. (14) as

$$\frac{dT}{dz} = -\frac{g}{C_p} \quad (15)$$

Eq. (15) gives the temperature lapse rate for dry parcel of air moving upwards adiabatically and is known as the dry adiabatic lapse rate (DALR)

Thus DALR, which is denoted by Γ , is found to be

$$\Gamma = \left(\frac{dT}{dz} \right)_{adia} = 10^\circ C / 1km \quad (16)$$

The environmental lapse rate (ELR) is denoted by, $\left(\frac{dT}{dz} \right)_{env}$

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ELR is change of temperature with altitude for a stable atmosphere where as DALR is the change in temperature of a mass of air as it moves upwards.

DALR is extremely important in studying the stability of the atmosphere.

Atmospheric stability

The ability of the atmosphere to disperse the pollutant emitted into it depends to a large extent on the degree of its stability. A comparison the adiabatic lapse rate with the environmental lapse rate (or compare the parcel's temperature T_p with the temperature of the surrounding environment T_e), gives an idea of the stability of the atmosphere. The figure below (Fig,1) illustrates the temperature profile for various cases of stability.

The cases of stability can be explained as:

1. **Very stable:** Temperature increases with increasing in altitude. This is an inversion. Such a lapse rate is known as the negative lapse rate. Under these conditions, the atmosphere is very stable and practically no mixing of pollutants takes place.
2. **Stable:** When $ELR < DALR$ ($T_e > T_p$) a rising air parcel becomes cooler and more dense than its surroundings and tends to fall back to its original position, in this condition the lapse rate is said to be **subadiabatic**. Under stable condition there is very little vertical mixing (less buoyancy) and pollutants disperse very slowly
3. **Neutral stable:** When the $ELR = DALR$, ($T_e = T_p$), a rising parcel of air will have the same temperature, pressure and density of the surrounding and would experience no buoyancy force. In this case a displaced mass of air neither tends to return to its original position nor tends to continue its displacement.
4. **Unstable:** When the $ELR > DALR$, ($T_e < T_p$), the atmospheric is said to be **superadiabatic**. Hence, a rising parcel of air will be warmer and less dense than the surrounding environment. As a result, it becomes more buoyant and tends to continue its upward motion. In unstable atmosphere the Air from different altitude mixes thoroughly. This is very desirable from the point of view of preventing pollution, since the effluents will be rapidly dispersed throughout the atmosphere.
5. **Condition stability CS:** occurs if the environmental lapse rate is between the two values of stability and instability.

Note:**1. When the atmosphere is stable?**

the atmosphere is stable when, a parcel of air will want to return to its original after being rising.

2. When the atmosphere is unstable?

the atmosphere is unstable when, a parcel of air will want to continue on its path away from its original position.

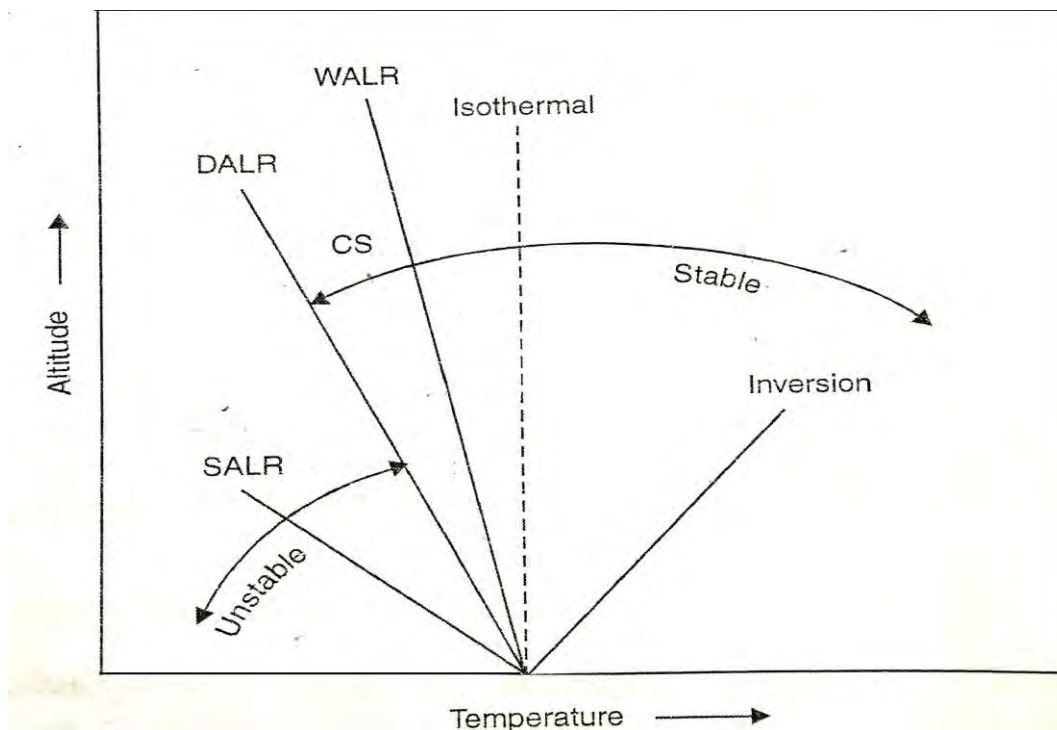


Fig.12. Atmospheric stability regions (SALR: Super-adiabatic lapse rate; DALR: Dry adiabatic lapse rate; WALR: Wet adiabatic lapse rate; CS: Conditional stability)

Inversions

Temperature inversion, condition in which the temperature of the atmosphere increases with altitude, in contrast to the normal decrease with altitude.

When temperature inversion occurs, cold air underlies warmer air at higher altitudes.

Under this condition the atmosphere is very stable and practically no mixing of pollutants takes place.

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Wind speed:

Wind speed is caused by air moving from high pressure to low pressure. The wind velocity is influenced by: (1) the surface roughness, (2) the time of the day.

Atmospheric turbulence

Atmospheric turbulence is irregular air motions characterized by wind that vary in speed and direction. Turbulence is important because it mixes and churns the atmosphere and causes water vapor, smoke, and other substances, as well as energy, to become distributed both vertically and horizontally.

Plume behavior

The behavior of plume emitted from an elevated source such as a tall stack depends on:

- 1- The degree of instability of the atmosphere,
- 2- The prevailing wind turbulence.

Plume Types

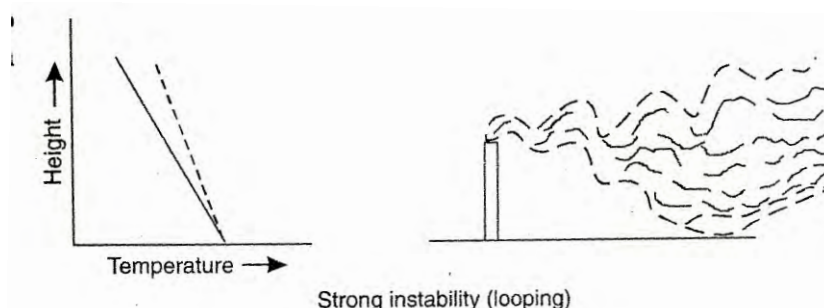
The Common types of plume behavior under various conditions of stability are:

- | | |
|------------------|---------------------|
| 1- Looping plume | 4- fumigation plume |
| 2- coning plume | 5- lofting plume |
| 3- fanning plume | 6- trapping plume |

The first three types of plume behavior (looping, coning, and fanning) are observed under conditions of uniform lapse rate.

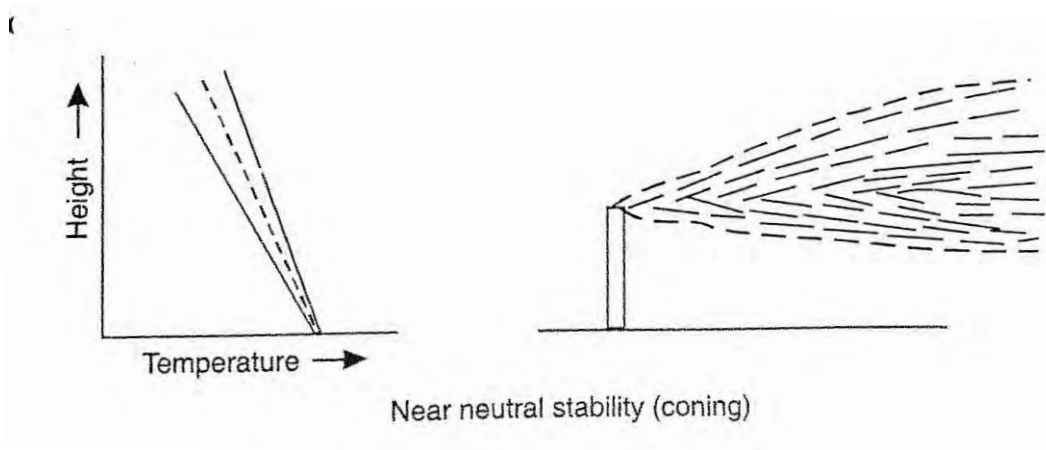
The others plumes (fumigation, lofting, and trapping) are observed when the lapse rate changes from stable to unstable

1. **Looping plume:** It occurs under superadiabatic conditions with light to moderate wind speeds on a hot summer afternoon when large scale thermal eddies are present. These eddies carry portions of plume to the ground level for short time periods, causing momentary high surface concentration of pollution near the stack.

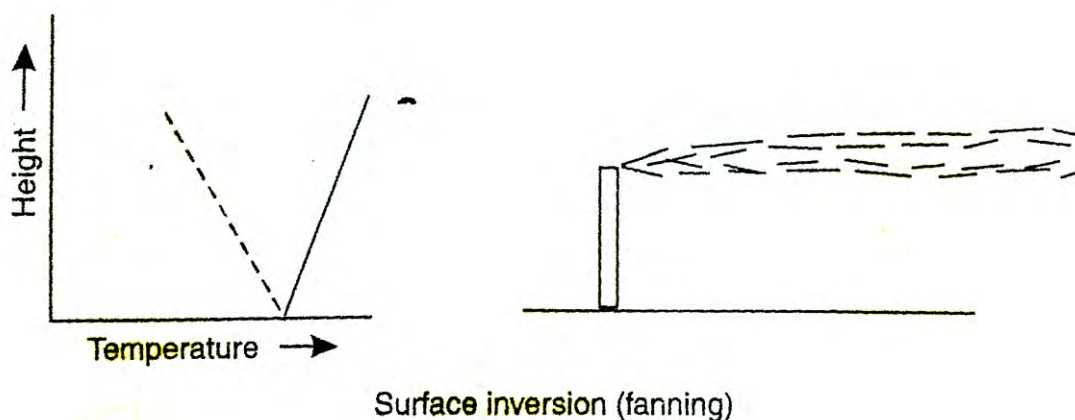


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2. **Coning plume:** It can occur under cloudy skies both during day and night when the lapse rate essentially neutral. The plume shape is vertically symmetrical about the plume line and a major part of pollutant concentration is carried downwind fairly far before reaching the ground level. Coning is often associated with moderate to high wind speeds.



3. **Fanning plume:** It occurs when the plume is dispersed in the presence of very light winds as a result of strong atmospheric inversions. If the density of the plume is not significantly different from that of the surrounding atmosphere, the plume travels parallel to the ground in a flat, straight ribbon downwind. For high stack, fanning is considered a favorable because the plume does not contribute to ground pollution. A fanning plume is often observed at height and in early morning in all seasons.



Air dispersion model

Air dispersion model is a mathematical simulation of how pollutants dispersed in the ambient atmosphere. The dispersion models are used to estimate or to predict the downwind concentration of air pollutants from sources such as industrial plants. One of the most models is the Gaussian plume model.

Gaussian plume Model

The Gaussian plume idea

Gaussian plume model is usually called as diffusion model and sometimes dispersion model. In this model:

- a point source such as a factory smoke stack is selected
- the downwind concentration resulting from this point source is calculated.

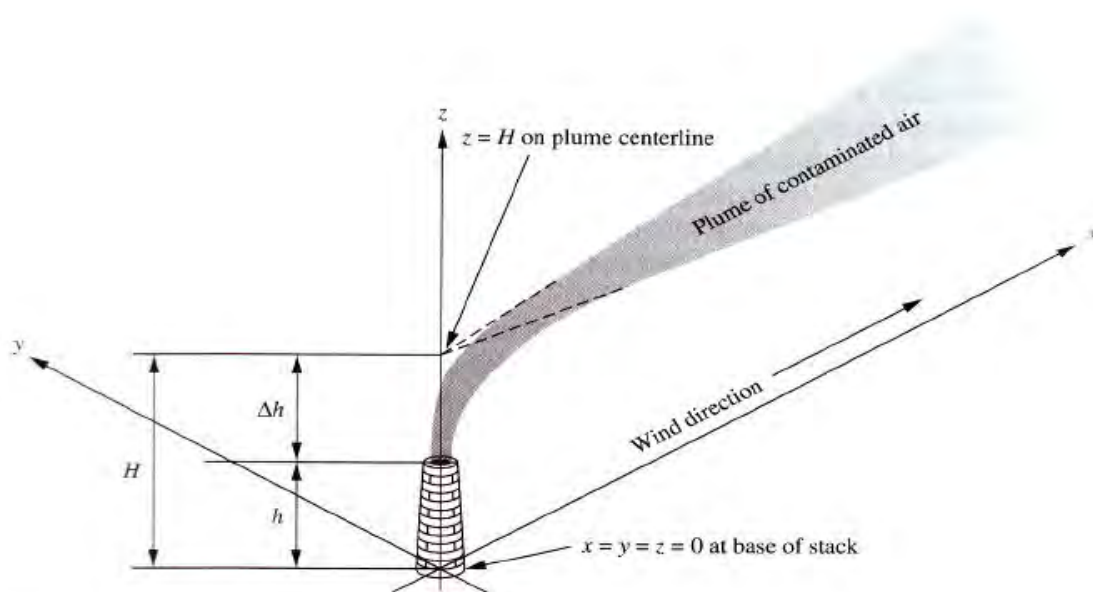


Fig. 13. Coordinate system for Gaussian plume idea

From Fig. 13.:

- The origin of the coordinate system is placed at the base of the smokestack with x -axis aligned in the downwind direction. The contaminated gas stream or plume rising from the smoke stack (Δh) and then travel in x direction and spread in the y and z direction as it travels.

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- The plume normally rises higher above the smokestack because they are emitted at higher temperature than atmosphere and with vertical velocity.
- Plume rise caused by : 1. buoyancy force, 2. Vertical momentum.
- For calculation, the plume is assumed to be emitted at coordinate. $(0, 0, H)$, where H is effective stack height. Where H is effective stack high as illustrate in Fig. 14.

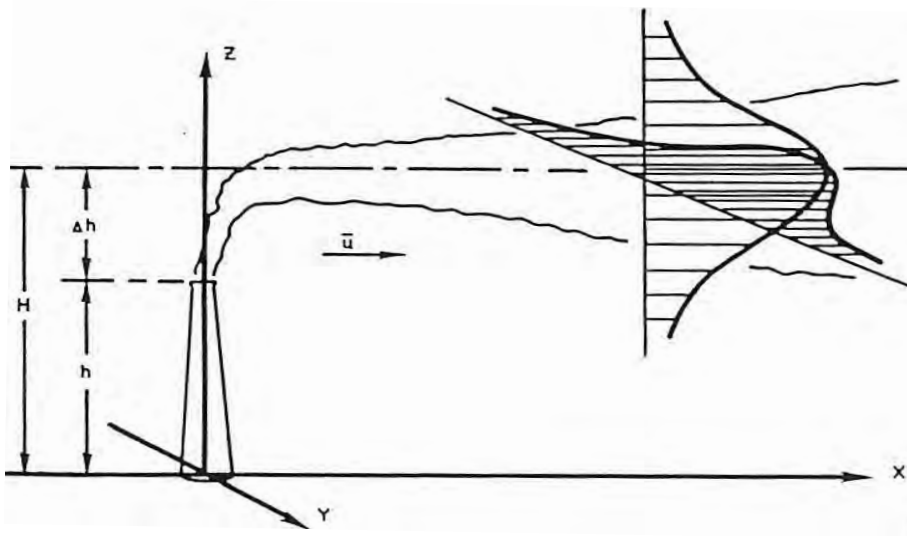


Fig.14. Gaussian Dispersion Model

- The effective stack height is the summation of physical stack height, h , and plume rise, Δh : $H = h + \Delta h$

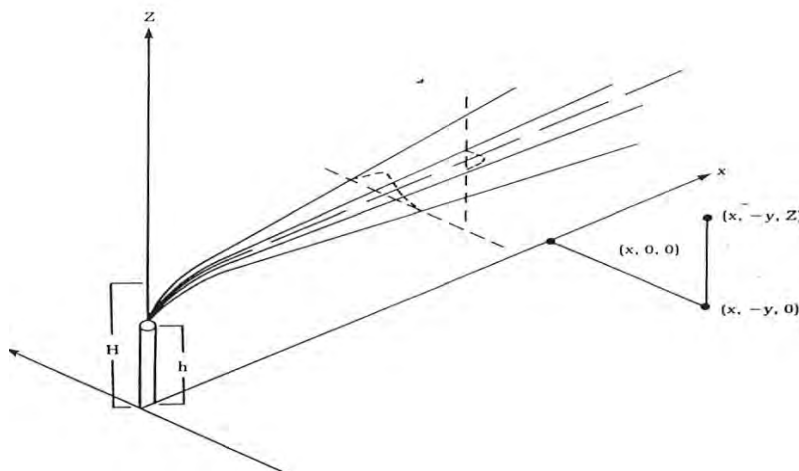


Fig.15. Plume dispersion Coordinate system

Gaussian dispersion equation

❖ Extension to elevated sources with reflection

Most pollutants are emitted into atmosphere from elevated sources such as chimney stacks so that the **equation for pollutant concentration at selected location (x, y, z) in three dimensional field downwind of the elevated point source is given by:**

$$C(x, y, z, H) = \underbrace{\frac{Q}{2\pi\sigma_y\sigma_z\bar{u}}}_{\text{Centerline}} \underbrace{\exp\left(-\frac{1}{2}\frac{y^2}{\sigma_y^2}\right)}_{\text{Horizontal}} \underbrace{\left\{\exp\left(-\frac{1}{2}\frac{(z-H)^2}{\sigma_z^2}\right) + \exp\left(-\frac{1}{2}\frac{(z+H)^2}{\sigma_z^2}\right)\right\}}_{\text{Vertical}} \quad (17)$$

where

σ_y & σ_z : horizontal and vertical dispersion coefficient
=f (downwind distance x & atmosphere stability), m

C: pollutant concentration, $\mu\text{g}/\text{m}^3$

Q: pollutant emission rate. g/s

H: effective stack height. M

u: wind velocity, m/s

σ_y : Horizontal crosswind dispersion coefficient, m

σ_z : vertical crosswind dispersion coefficient, m

Eq.17 consists of three terms:

1. Centerline concentration as a function of downwind distance, x
2. The lateral spread relative to the centerline value (horizontal), y
3. The vertical spread relative to the centerline value. z

The first term in Eq.18 $\left(\frac{Q}{2\pi\sigma_y\sigma_z\bar{u}}\right)$ is the concentration in the centerline of the plume.

The two values increase with downwind distance, so that the centerline concentrations decrease with downwind distance.

The second and third terms (the exponential term) show how the concentration decreases as we move horizontally or vertically.

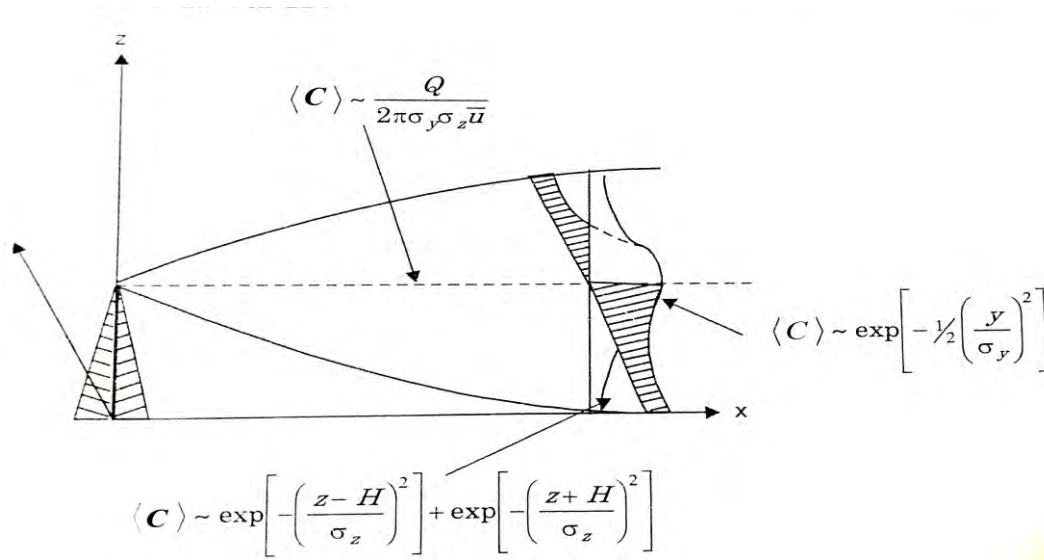


Fig.16. representation of the centerline concentration terms and lateral and vertical terms

Three common forms obtained from the basic equation are frequently used to analyze specific situations:

a) Ground level concentration ($z = 0$) - plume at height H

$$C(x, y, 0, H) = \frac{Q}{\pi\sigma_y\sigma_z\bar{u}} \exp\left(-\frac{1}{2} \frac{y^2}{\sigma_y^2}\right) \exp\left(-\frac{1}{2} \frac{H^2}{\sigma_z^2}\right) \quad (18)$$

b) Ground level centerline concentration: ($z = 0$) and ($y = 0$) - plume height H

$$C(x, 0, 0, H) = \frac{Q}{\pi\sigma_y\sigma_z\bar{u}} \exp\left(-\frac{1}{2} \frac{H^2}{\sigma_z^2}\right) \quad (19)$$

Eq.19 is used to estimate the ground level concentration expected at any distance of any elevated source.

In the case of emission source is also at the ground level, i.e., $H = 0$. Eq. 19 further simplifies to

$$C(x, 0, 0, 0) = \frac{Q}{\pi\sigma_y\sigma_z\bar{u}} \quad (20)$$

c) Maximum ground level centerline concentrations from an elevated source

The maximum ground level concentration can be obtained starting from Eq.19. If the spreading coefficient σ_y and σ_z are expressed as:

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$$\sigma_y = Ax^p \quad (21)$$

and $\sigma_z = Bx^p \quad (22)$

where A, B and p are constants, then the value of $\langle C \rangle$ in Eq.19 can be maximized by substituting for σ_y and σ_z and setting $\frac{dC}{dx} = 0$. Then simplification of resulting expression yields:

$$\frac{-2p}{x^{2p+1}} + \frac{H^2 p}{B^2 x^{4p+1}} = 0 \quad (23)$$

From Eq.21:

$$Bx^p = \sigma_z = \frac{H}{\sqrt{2}} \quad (24)$$

This gives the downwind position at which the maximum ground level centerline concentration occurs. Substituting of $\sigma_z = \frac{H}{\sqrt{2}}$ in Eq.19 we get:

$$C_{Max}(x,0,0,H) = \frac{2Q}{\pi \bar{u} e H^2} \frac{\sigma_z}{\sigma_y} \quad (25)$$

Eq.25 shows why pollutants are emitted into the atmosphere through tall stacks.

Note: e means exponent (exp. (1)) = 2.718.

Estimation of σ_y and σ_z

- The values of σ_y and σ_z are the dispersion coefficient in the y- and z-direction. They are function of downwind distance x from the source as well as to the atmospheric stability conditions.
- Based on experimental observations of the dispersion of real plume, σ_y and σ_z of the plume can be calculated from knowledge of the atmosphere stability.
- Six categories of atmospheric stability, A through F, were suggested as shown in table 1
- When the stability category is known from appropriate weather conditions σ_y and σ_z values for any downwind distance x can be calculated from the equations:

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$$\sigma_y = Ax^{0.903} \quad (26)$$

$$\sigma_z = Bx^p \quad (27)$$

Table 5 Key to Stability Categories

Wind speed (m/s) (at z =10 m)	Day			Night	
	Incoming solar radiation			Thin overcast ($\geq 4/8$ low cloud)	Clear ($\leq 3/8$ cloud)
	Strong	Moderate	Slight		
< 2	A	A-B	B	E	F
2-3	A-B	B	C	E	F
3-5	B	B-C	C	D	E
5-6	C	C-D	D	D	D
> 6	C	D	D	D	D

A: Extremely unstable, B: Moderately unstable, C: slightly unstable, D: Neutral conditions, E: Slightly stable, F: Moderately stable

The values of A, B and p are given in table 6

Table 6. Fitted values for σ_y and σ_z

Class	A	x_1 (meters)	$x \leq x_1$		x_2 (meters)	$x_1 \leq x \leq x_2$	
			B	p		B	p
A	0.40	250	0.125	1.03	500	0.00883	1.51
B	0.295	1000	0.119	0.986	10000	0.0579	1.09
C	0.20	1000	0.111	0.911	10000	0.111	0.911
D	0.13	1000	0.105	0.827	10000	0.392	0.636
E	0.98	1000	0.100	0.778	10000	0.373	0.587

The values in table 2 closely fit the curves shown in Figs. 17 and 18

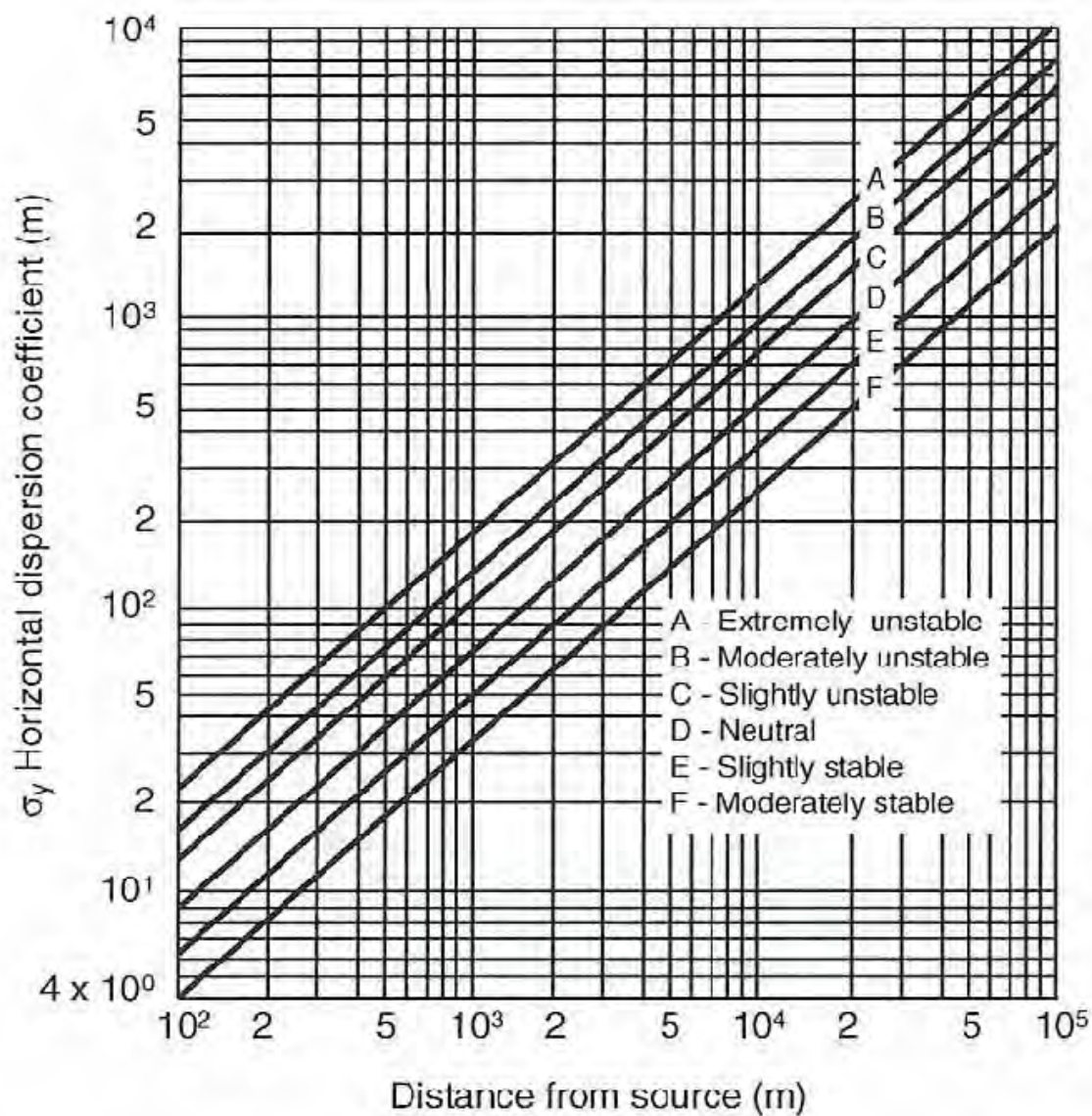
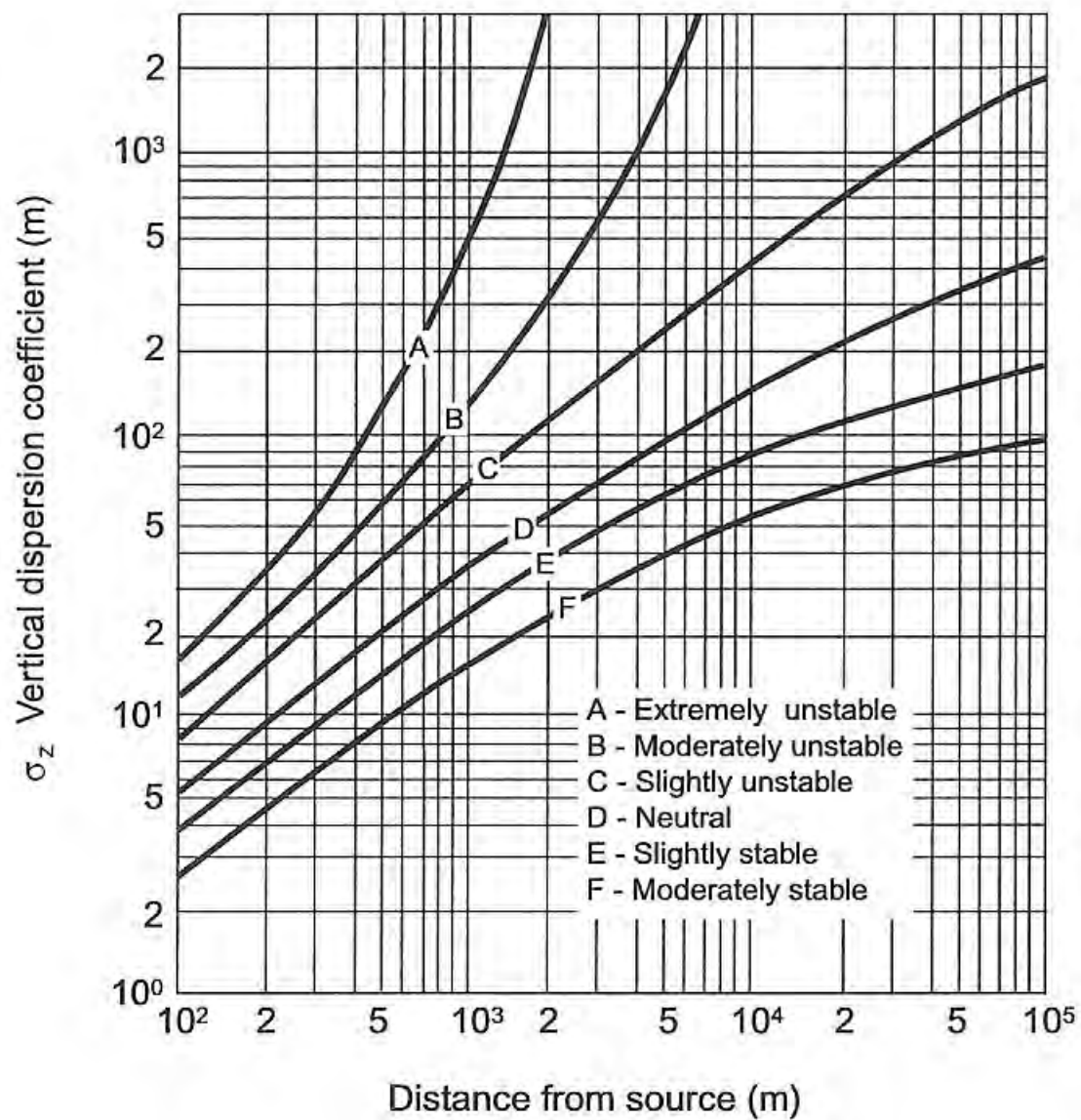


Fig.17 Horizontal Dispersion Coefficient σ_y

Fig.18 Vertical Dispersion Coefficient σ_z

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Figs 17 and 18 are adequate representations of the experimental results

Example (1):

Estimate the values of σ_y and σ_z at a point of 0.7 km downwind from a pollutant source on a bright sunny day (C category) with the wind speed 6 m/s.

Answer:

Using Figs. 17 and 18 we get:

$$\sigma_y = 70 \text{ m and } \sigma_z = 45 \text{ m}$$

Example (2):

A factory emits 20 g/s of CO at effective height (H) = 20 m. The wind speed is 5 m/s at distance 0.5 km downwind for C stability. What are the CO concentration at a point of 25m to the side and 2 m above the ground?

Solution

$$H = 20; \quad Q = 20 \text{ g/s}; \quad u = 5 \text{ m/s}$$

From Figs. 17 and 18 reading for σ_y and σ_z :

$$\sigma_y = 50 \text{ m and } \sigma_z = 37 \text{ m}$$

then substitute into Eq.18

$$C = \frac{Q}{2\pi\sigma_y\sigma_z\bar{u}} \exp\left(-\frac{1}{2} \frac{y^2}{\sigma_y^2}\right) \left\{ \exp\left(-\frac{1}{2} \frac{(z-H)^2}{\sigma_z^2}\right) + \exp\left(-\frac{1}{2} \frac{(z+H)^2}{\sigma_z^2}\right) \right\} \quad (18)$$

$$C = \frac{20 \text{ g/s}}{2\pi(50\text{m})(37\text{m})(5\text{m/s})} \exp\left(-\frac{1}{2} \frac{(25\text{m})^2}{(50\text{m})^2}\right) \left\{ \exp\left(-\frac{1}{2} \frac{(2-20)^2}{(37\text{m})^2}\right) + \exp\left(-\frac{1}{2} \frac{(2+20)^2}{(37\text{m})^2}\right) \right\}$$

$$C = 4.96 \times 10^{-4} \frac{\text{g}}{\text{m}^3} = 496 \frac{\mu\text{g}}{\text{m}^3}$$

So the concentration at $y = 25 \text{ m}$ and $z = 2 \text{ m}$ is $496 \mu\text{g/m}^3$.

Average wind speed \bar{u}

The average wind speed at stack height H can be evaluated by

$$\frac{\bar{u}}{\bar{u}_1} = \left[\frac{H}{z_1} \right]^\alpha \quad (28)$$

Where \bar{u}_1 is usually the meteorological value of the velocity at $z_1 = 10$ m, and \bar{u} are the wind speeds at altitude H .

$\alpha = 0.25$ for unstable conditions,

$\alpha = 0.50$ for stable conditions.

Note: the Gaussian model is most accurate for the downstream between approximately 100 and 2000 m.

Example (3):

A chimney with a design stack height of 250 m is emitting sulfur dioxide at a rate of 500 g/s on a sunny day in June with moderate wind speed at stack altitude. If the moderate wind speed at this condition is 6 m/s. Estimate the concentration of sulfur dioxide downstream for the following situations:

- (a) $\langle C_{SO_4} \rangle (1000, 0, 0, 250)$
- (b) $\langle C_{SO_4} \rangle (1000, 50, 0, 250)$
- (c) $\langle C_{SO_4} \rangle (1000, 50, 20, 250)$
- (d) If $\langle C_{SO_4} \rangle (1000, y, 0, 250)$ is $100 \mu\text{g}/\text{m}^3$, what is the value of y in meters?

solution:

on sunny day in June the incoming solar radiation will be strong, also the air will be unstable.

$$\bar{u} = 6 \text{ m/s}$$

From Eq.28 the velocity \bar{u}_1 at 10 m level can be obtained.

$$\bar{u}_1 = \bar{u} \left[\frac{z_1}{H} \right]^\alpha$$

For unstable condition $\alpha = 0.25$, therefore,

$$\bar{u}_1 = 6 \left[\frac{10}{250} \right]^{0.25} = 2.7 \text{ m/s}$$

This shows that the surface wind speed is between 2 and 3 m/s.

Reference to Table 1 shows a stability class of A-B. We choose class B

From the information given in Table 2, at class B and at distance $x = 1000$ m:

$$A = 0.295, \quad B = 0.119, \quad P = 0.986$$

Then the values of σ_y and σ_z can be calculated using Eqs. 26 and 27 respectively.

$$\sigma_y = Ax^{0.903} \quad (26)$$

$$\sigma_y = 0.295(1000)^{0.903} = 151 \text{ m}$$

And

$$\sigma_z = Bx^p \quad (27)$$

$$\sigma_z = 0.119(1000)^{0.986} = 108 \text{ m}$$

$$(a) \left\langle C_{SO_4} \right\rangle (1000, 0, 0, 250)$$

Using the ground level centerline equations Eq.20, substituting the values of σ_y and σ_z and using $Q = 500$ g/s, $\bar{u} = 10$ m/s, and $H = 250$ m, we get

$$C(x,0,0,H) = \frac{Q}{\pi \sigma_y \sigma_z \bar{u}} \exp \left(-\frac{1}{2} \frac{H^2}{\sigma_z^2} \right) \quad (20)$$

$$C(1000,0,0,250) = \frac{500 \times 10^6}{\pi (151)(108)6} \exp \left(-\frac{1}{2} \frac{(250)^2}{(108)^2} \right) = 112 \times 10^{-4} \frac{\text{g}}{\text{m}^3} = 112 \mu\text{g} / \text{m}^3$$

(b) $\langle C_{SO_4} \rangle$ (1000, 50, 0, 250)

Using Eq.19, we get

$$C(x, y, 0, H) = \frac{Q}{\pi \sigma_y \sigma_z \bar{u}} \exp\left(-\frac{1}{2} \frac{y^2}{\sigma_y^2}\right) \exp\left(-\frac{1}{2} \frac{H^2}{\sigma_z^2}\right) \quad (19)$$

$$C(1000, 50, 0, 250) = \frac{500 \times 10^6}{\pi(151)(108)6} \exp\left(-\frac{1}{2} \frac{(50)^2}{(151)^2}\right) \exp\left(-\frac{1}{2} \frac{(250)^2}{(108)^2}\right) = 106 \times 10^{-4} \frac{g}{m^3} = 106 \mu g / m^3$$

$\langle C_{SO_4} \rangle$ (1000, 50, 20, 250)

Using Eq.18, we get

$$C(x, y, z, H) = \frac{Q}{2\pi \sigma_y \sigma_z \bar{u}} \exp\left(-\frac{1}{2} \frac{y^2}{\sigma_y^2}\right) \left\{ \exp\left(-\frac{1}{2} \frac{(z-H)^2}{\sigma_z^2}\right) + \exp\left(-\frac{1}{2} \frac{(z+H)^2}{\sigma_z^2}\right) \right\} \quad (18)$$

$$C(1000, 50, 20, 250) = \frac{500 \times 10^6}{2\pi(151)(108))} \exp\left(-\frac{1}{2} \frac{(50)^2}{(151)^2}\right) \times$$

$$\left\{ \exp\left(-\frac{1}{2} \frac{(20-250)^2}{108^2}\right) + \exp\left(-\frac{1}{2} \frac{(20+250)^2}{108^2}\right) \right\} = 113 \times 10^{-4} \frac{g}{m^3} = 113 \mu g / m^3$$

(c) If $\langle C_{SO_4} \rangle$ (1000, y, 0, 250) is 100 $\mu g/m^3$, what is the value of y in meters?

Dividing Eq.19 by Eq.20, we get

$$\frac{\langle C_{SO_2} \rangle(1000, 50, 0, 250)}{\langle C_{SO_2} \rangle(1000, 0, 0, 250)} = \exp\left[\frac{1}{2} \frac{y^2}{\sigma_y^2}\right]$$

$$y = \left[2 \ln \frac{\langle C_{SO_2} \rangle(1000, 0, 0, H)}{\langle C_{SO_2} \rangle(x, y, 0, H)} \right]^{1/2} \sigma_y$$

$$y = \left[2 \ln \frac{\langle C_{SO_2} \rangle(1000, 0, 0, H)}{\langle C_{SO_2} \rangle(x, y, 0, H)} \right]^{1/2} \quad (151)$$

$$y = \left[2 \ln \frac{112}{100} \right]^{1/2} (151) = 72m$$

Effective Stack Height

Generally, effluent plumes from chimney stacks are released into the atmosphere at elevated temperature. The rise of the plume after release to the atmosphere is caused by the buoyancy and vertical momentum of the effluent. Under windless conditions the plume rises vertically but more often it is bent as a result of the wind that is usually present. This rise of the plume adds to the stack an additional height, ΔH , such that the effective stack height, H is obtained by adding the term ΔH , the plume rise, to the actual height of the stack (physical height), h . The plume centerline height $H = H_s + \Delta H$ is known as the effective stack height and it is the height that is used in Gaussian plume calculations. The effective stack height is illustrated in Fig.8

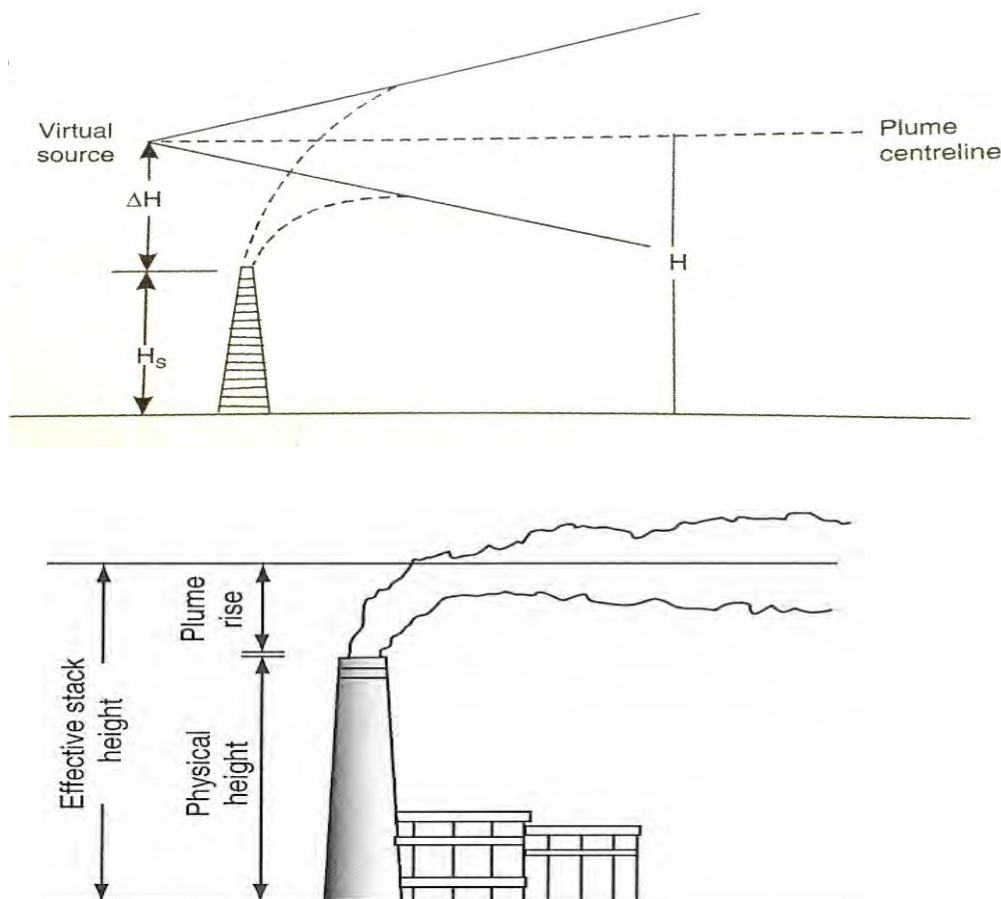


Fig.19 plume rise

The effective stack height is given by

$$H = H_s + \Delta H \quad (29)$$

Where

H : is the effective stack h

H_s : is the actual or physical stack height

ΔH : is the plume rise

Estimation of Plume Rise

The plume rise ΔH is essentially used to estimation the effective stack height. The common formulas used to estimate the plume rise are:

1. Buoyant plumes
2. Non- buoyant plumes
3. Plume rise for larger volume source

1. Buoyant plumes

The influence of buoyancy force is greater than the influence of vertical momentum. Such plumes are usually when the release temperature are more than 50 °C greater than ambient atmospheric temperatures.

1- Holland equation

This is one of the earliest equations proposed to calculate the plume rise. It has been widely used because of its simplicity and has been included in many plume rise studies.

$$\Delta H = \frac{(1.5V_s D_s + 4 \times 10^{-5} Q_H)}{\bar{u}} \quad (30)$$

where

V_s : Stack gas exit velocity, m/s

D_s : Diameter of stack outlet, m

\bar{u} : Wind velocity, m/s

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Q_H : Heat emission rate, cal/s

ΔH : Plume rise above the stack, m

Eq.30 may also be expressed as reported by Turner

$$\Delta H = \frac{V_s D_s}{\bar{u}} \left(1.5 + 2.68 \times 10^{-3} p_a \frac{T_s - T_a}{T_s} D_s \right) \quad (31)$$

where

p_a : atmospheric pressure, mbar

T_s : stack gas temperature, K

T_a : ambient air temperature at stack height, K

2. Non-Buoyant plumes

For sources at temperature close to the ambient and having exit speeds of at least 10 m/s.

$$\Delta H = D_s \left(\frac{V_s}{\bar{u}} \right)^{1.4} \quad (32)$$

3. Plume rise for larger volume source

For volumes flow rates greater than 50 m³/s, for unstable or neutral conditions, the recommended equation is

$$\Delta H = 150 \frac{F}{(\bar{u})^3} \quad (33)$$

where, F is the buoyancy flux parameter (m⁴/s³), given by

$$F = g V_s \left(\frac{D_s}{2} \right)^2 \frac{T_s - T_a}{T_s} \quad (34)$$

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Example (4):

Estimate the plume rise for a 2 m diameter stack and the exit gas has a velocity of 34 m/s when the wind velocity is 4 m/s, the pressure is 1 atm and the stack and surrounding temperatures are 85 °C and 33 °C respectively.

Answer:

Eq. 30

$$\Delta H = \frac{V_s D_s}{\bar{u}} \left(1.5 + 2.68 \times 10^{-3} p_a \frac{T_s - T_a}{T_s} D_s \right) \quad (31)$$

$$\Delta H = \frac{(34 \text{ m/s})(2 \text{ m})}{4 \text{ m/s}} \left(1.5 + 2.68 \times 10^{-3} \times 1013 \times \frac{(358 \text{ K} - 306 \text{ K})}{358 \text{ K}} \times 2 \right) = 38.9 \text{ m}$$

Example (5):

A chimney with a design stack height of 250 m is emitting sulfur dioxide at a rate of 500 g/s on a sunny day in June with moderate wind speed at stack altitude. The stack diameter is 5 m, the sulfur dioxide exit velocity is 13.5 m/s, and the gas temperature of the exit is 145 °C. If the wind speed at this condition is 6 m/s, what is the plume rise for an ambient air temperature of 30 °C. Calculate the ground level concentration of sulfur dioxide on the plume centerline at the downstream distance of 1 km. the density of sulfur dioxide at 145 °C is 1.886 kg/m³

solution:

Calculate the volumetric flow rate of the flue gas:

$$\begin{aligned} \text{Vol.Flow.Rate} &= V_s \times A_s = V_s \times \left(\frac{\pi}{4} D_s^2 \right) \\ \text{Vol.Flow.Rate} &= (13.5 \text{ m/s}) \times \left[\frac{\pi}{4} (5)^2 \right] = 265 \text{ m}^3 / \text{s} \end{aligned}$$

Where A_s is the cross section area of the exit stack

Since the volumetric flow rate is far greater than 50 m³/s, Eq.33 can be applied

$$\Delta H = 150 \frac{F}{(\bar{u})^3}$$

The buoyancy flux F parameter is given by Eq.34

$$F = g V_s \left(\frac{D_s}{2} \right)^2 \frac{T_s - T_a}{T_s}$$

$$F = 9.8(13.5) \left(\frac{5}{2} \right)^2 \frac{418 + 303}{418} = 227 m^4 / s^3$$

Then
$$\Delta H = 150 \frac{227}{(6)^3} = 158 m$$

The effective stack height H is

$$H = H_s + \Delta H = 250 + 158 = 408 m$$

Using the value of H in Eq.20, we get

$$C(x,0,0,H) = \frac{Q}{\pi \sigma_y \sigma_z \bar{u}} \exp \left(-\frac{1}{2} \frac{H^2}{\sigma_z^2} \right) \quad (20)$$

$$C(1000,0,0,408) = \frac{500(10^6)}{\pi(151)(108)6} \exp \left(-\frac{1}{2} \frac{(408)^2}{(108)^2} \right) = 1.30 \mu g / m^3$$

Note: the values of σ_y and σ_z are taken from Example 3

There is a significant reduction in ground level concentration as compared to the case for zero plume rise, means $H = 250+0 = 250$, where

$$C(1000,0,0,250) = \frac{500(10^6)}{\pi(151)(108)6} \exp \left(-\frac{1}{2} \frac{(250)^2}{(108)^2} \right) = 112 \mu g / m^3$$

Example (6):

The heat emission rate associated with a stack gas is 4800 kJ/s, the wind and stack gas speed are 5 m/s and 15 m/s respectively. The inside stack diameter at the top is 2 m. Estimate the plume rise.

Answer:

Using Holland equation, Eq.30

$$\Delta H = \frac{(1.5V_s D_s + 4 \times 10^{-5} Q_H)}{\bar{u}} \quad (30)$$

$$Q_H = 4800 \text{ kJ}$$

$$1 \text{ cal} = 4.184 \text{ J}$$

$$\text{Then } Q_H = (4800 \text{ kJ/s}) \times \frac{1 \text{ kcal}}{4.184 \text{ kJ}} = 1147 \text{ kcal/s} \times \frac{1000 \text{ cal}}{1 \text{ kcal}} = 1.147 \times 10^6 \text{ cal/s}$$

$$\Delta H = \left[\frac{1.5(15)(2) + 4 \times 10^{-5} (1.147 \times 10^6)}{5} \right] = 18.2 \text{ m}$$

Air pollution control equipment

The various air pollution control equipments are used to control the air pollution from stationary sources. These equipments are conveniently divided into two types, one type are those which applicable for controlling particulate, and the other that used for controlling gaseous pollutants as shown in Fig.20.

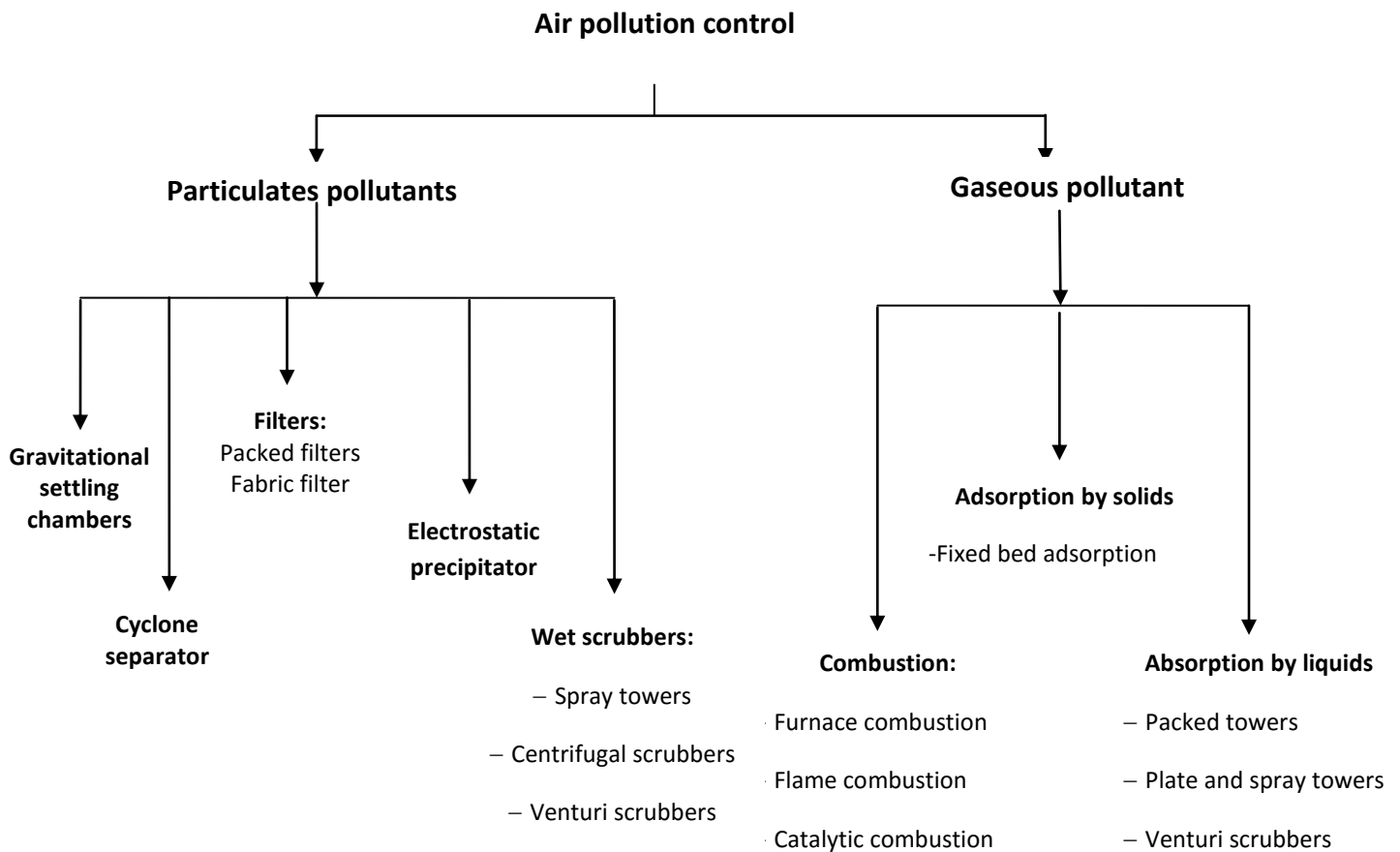


Fig.20. The most commonly equipments deal with air pollution control from stationary sources

Control of Particulate Pollutants

Particulate control equipment

Particulate matter emitted in gaseous streams consists of discrete and minute suspended particles. Particle sizes range from $100\ \mu\text{m}$ to $0.1\ \mu\text{m}$ and even less. The choice of collection devices depends upon a number of factors:

- 1- The physical and chemical properties of the particulates.
- 2- The range of volumetric flow rate of the gas stream.
- 3- The particulate size and its concentration in gas stream.
- 4- The temperature and humidity of the flow stream.
- 5- The toxicity and inflammability
- 6- The collection efficiency that required for outlet stream.

1- Gravitational settling cambers

Gravitational force may be employed to remove particulate

- 1) Used to remove of coarse particles larger than $50\ \mu\text{m}$ from gas streams,
- 2) Since most of particles in the gas stream are much smaller sizes than $50\ \mu\text{m}$, these devices are used as a primarily prior to passing the gas stream through high efficiency devices.
- 3) They offer low pressure drop and required simple maintenance.

The efficiency of equipment depends on the residence time of the gas in the settling chamber which is related to the velocity of the gas flow and the chamber volume. The simplest form of gravity settling camber is shown in Fig.21.

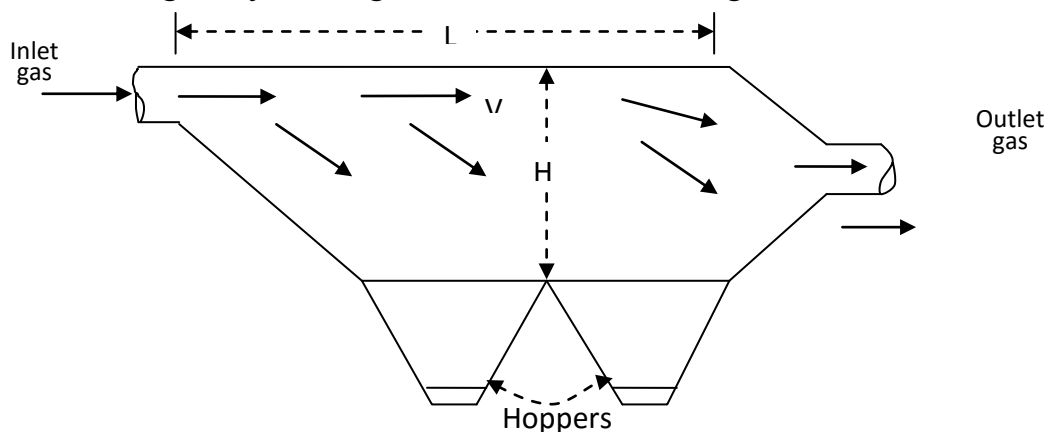


Fig.21. A gravitational settling chamber

2- Cyclone separators

Cyclone separators utilize a centrifugal force generated by spinning gas stream to separate the particulates from the carrier gas. The centrifugal force on particles in a spinning gas stream is much greater than gravity; therefore, cyclones are effective in the removal of much smaller particles than gravitational settling chambers, and required much less space to handle the same gas volumes.

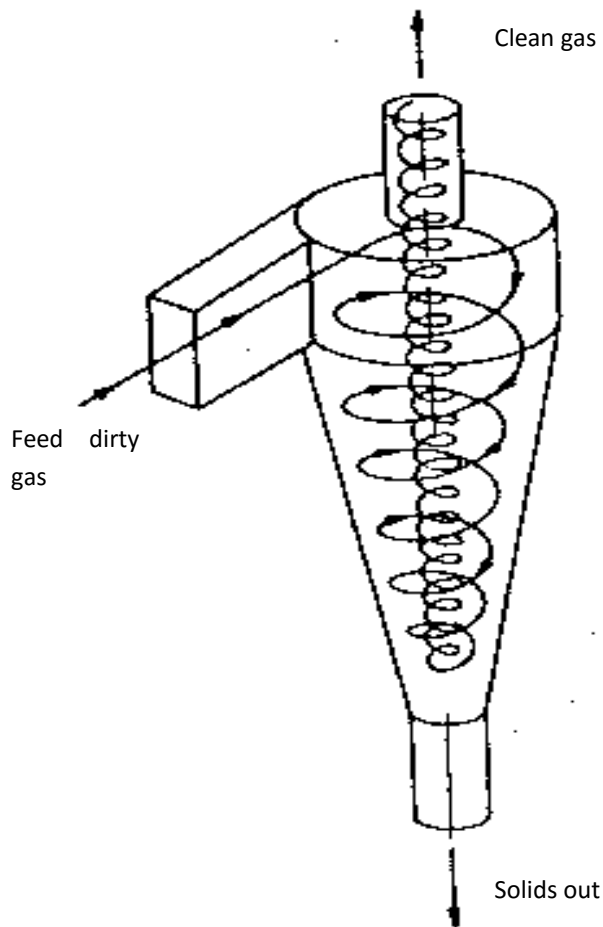


Fig.22. A cyclone separator

The dirty gas flows tangentially into the cyclone at the top, and spiral down near the outer radius and then back upward in the center core, in a second smaller diameter spiral, and exit at the top through a central vertical pipe. The particle moves radially to the walls, slide down the walls, and are collected at the bottom.

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Type of cyclones

Three types of cyclones:

1- Conventional cyclones

It is applied to remove particles of 25 μm or larger with an efficiency greater than 90%.

2- High efficiency cyclones

The inlet gas velocity is higher, thereby importing a higher centrifugal force. These types are effective with particle sizes down to 5 μm .

3- High volume cyclones

Particle sizes are generally larger than 50 μm are collected with great efficiency. They can handle larger flow.

Fig.23 shows typical curves for several types of equipment with their fractional collection efficiency as a function of particle size

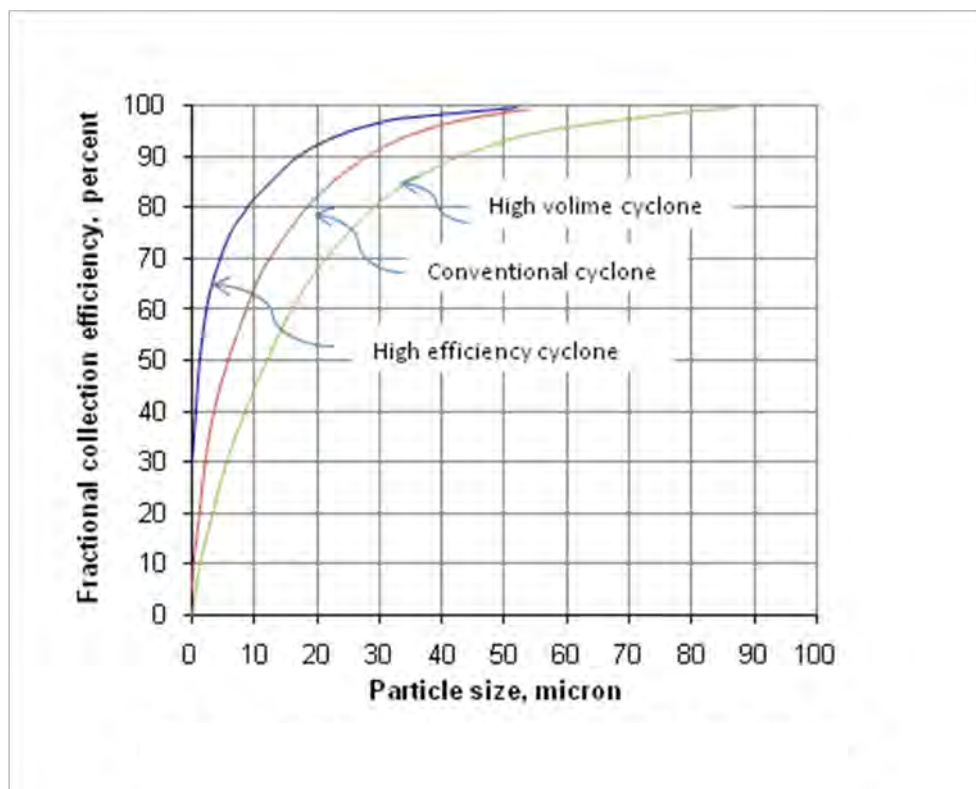


Fig.23. the fractional collection efficiency as a function of particle size for several types of cyclones.

3- Fabric filter (or bag filter)

Filtration is one of the oldest and most widely used methods of separating particulate from a carrier gas. A filter generally is a porous structure which tends to retain the particulate as the carrier gas passes through the void of filter, and allowing clean gas to pass out.

The fabric filter consists of several tubular bags or an envelope, called a baghouse, hanged in such a manner that the collected particle fall into a hopper. The dirty gas enters the bag at the bottom and passes through the fabric filter, while the particulate is deposited on the inside of the bag and the gas passes out from their side to be finely released out of the filter system as a clean gas. Fig.24 shows a typical baghouse.

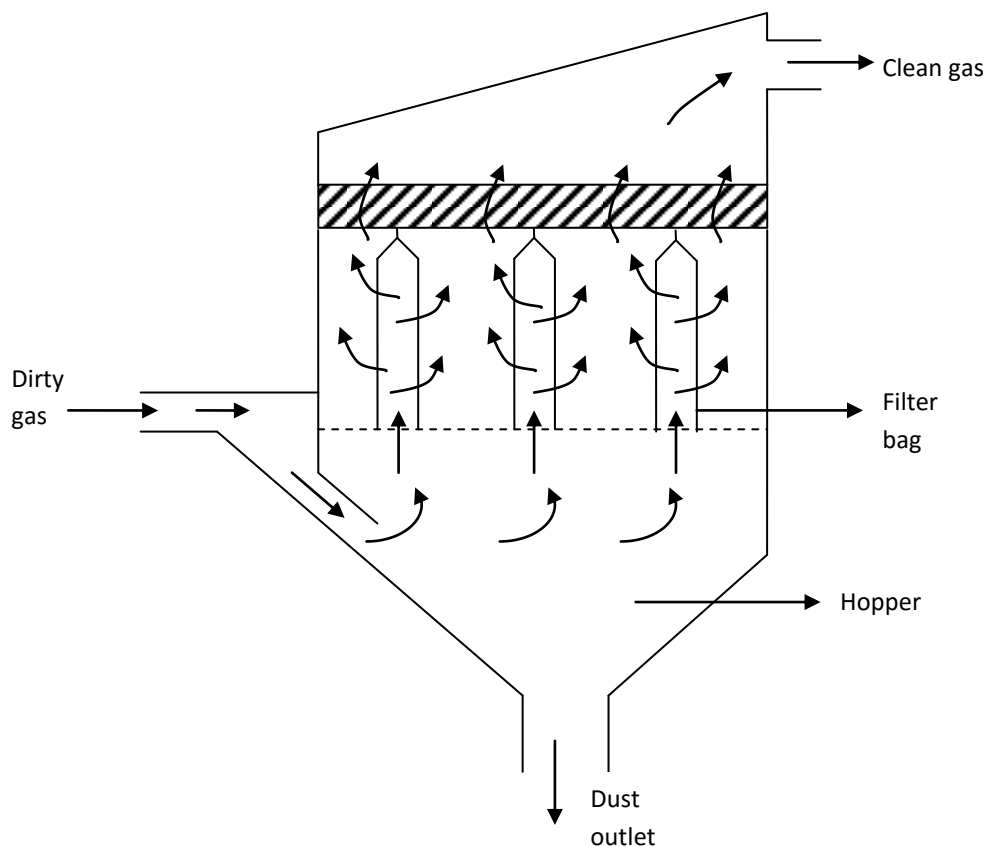


Fig.24. Typical bag house

The advantages of fabric filter

- 1- High collection efficiency over broad range of particle size.
- 2- Retention of finest particles.
- 3- Relatively low pressure drops.

4- Collection of particulates in dry form.

The main disadvantages of fabric filter

- 1- Their large size.
- 2- High construction costs.
- 3- Hygroscopic material cannot be handling.

4- Electrostatic precipitators, ESP

Electrostatic precipitator is a physical process by which particles suspended in gas stream are discharged electrically and, under the influence of the electrical field, separated from the gas stream. A typical wire and pipe precipitator is shown in Fig.25.

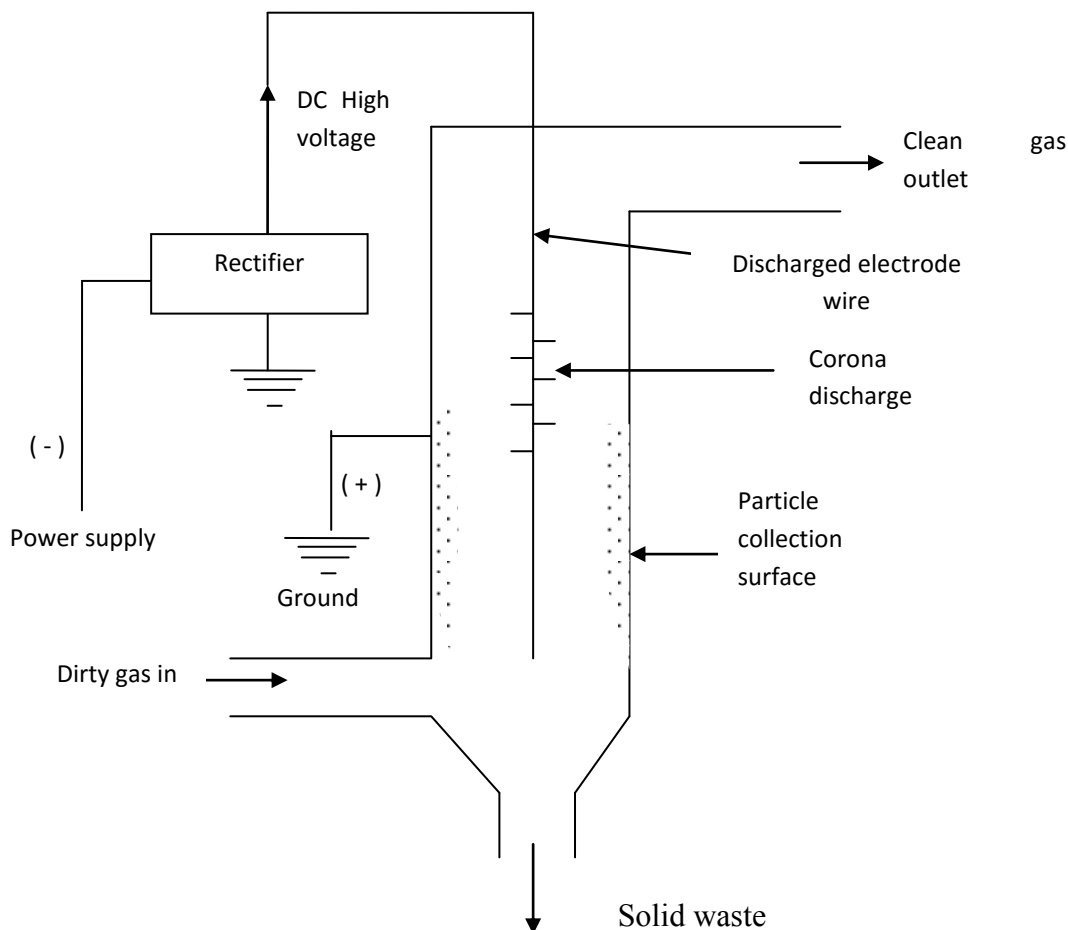


Fig.25. Electrostatic precipitators

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The ESP system consists of a positively charged (grounded) collecting surface and a high-voltage discharge electrode wire (negative electrode) suspended axially in the tube. At a very DC a corona discharge occurs close to the negative electrode, setting up an electric field between the wire electrodes and the collecting surface electrode. Electrons are released at the wire electrode in a corona discharge. As the particle-laden gas enters near the bottom and flows upward, these electrons attach themselves to particles to charge them. The charge particles are derived by the electric field toward the grounded surface of tube; on the surface the particles lose their charge and collection occur.

Advantages of electrostatic precipitators

- 1- Low Pressure drop
- 2- High collection efficiencies very small particles can be collected wet and dry.
- 3- Can handle both gas and mists for high volume flows.
- 4- Low energy consumption.
- 5- Ability to operate with relatively high temperature gases.

Disadvantages of electrostatic precipitators

- 1- Relatively high initial cost and large space requirement.
- 2- It is necessary to safeguard operating person from high voltage.
- 3- Collection efficiency can deteriorate (گتند هور) gradually.

5- Wet scrubbers

Wet scrubber is one of the particulate control equipment in which water is used to capture particulate dust. The resulting the solids are removed from the gas stream by water as slurry. The principle mechanism involved impact (impingement) of the dust particles and water droplet in order to achieve good contact time.

The advantages of wet scrubbers

- 1- Simultaneously removal of gases and particulate.
- 2- Can effectively remove fine particulate, both liquid and solid, ranging from 0.1-20 μm from gas stream.
- 3- Equipment occupies only a moderate amount of space compared to dry collectors such as bag house.

The disadvantages of wet scrubbers

- 1- Relatively high energy costs.
- 2- Problem of wet sludge disposal.

- 3- Corrosion problems
- 4- The wet sludge causes water pollution and there is need to treatment method to remove particles from the water.
- 5- Very small particles (sub-micron sizes) may not captured.

The major types of wet scrubbers are:

- 1- Spray scrubbers
- 2- centrifugal scrubbers
- 3- Venture scrubbers

1-Spray scrubbers

The simplest type of wet scrubbers is a spray tower (Fig.26) in which the polluted gas flows upward and water droplet is sprayed downward by means of spray nozzles located across the flow passage. The particle from the polluted gas is colliding with water droplet and the water droplet contaminated with this particle. If the gas flow rate is relatively slow, the contaminated water droplets will settle by gravity to the bottom of the tower as slurry. A mist eliminator is usually placed at the top of the tower to remove both exes clean water droplet and dirty droplets which are very small that cannot be settled and thus carried upward by the gas flow.

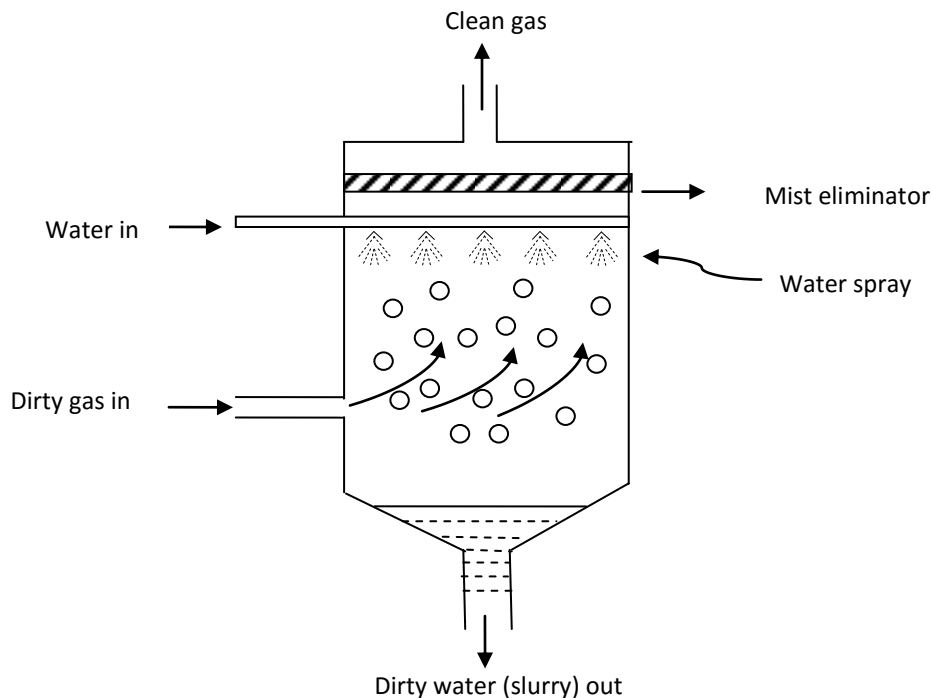


Fig.26. Sketch of a spray tower scrubber

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High pressure spray produce small droplet with more surface area per mass of water used. The effectiveness spray towers ranges from 95% for 5 μm particles 99% for 25 μm particles.

Spray tower is a counter current flow and may be circular or rectangular spray tower as shown in Fig.26.

2-Centrifugal scrubbers

Fig.16. shows centrifugal scrubber. The polluted gas introduced tangentially into the lower portion of the vertical cylinder. Water drops are injected from multiple nozzles, which throw the water radially outward across the flow gas stream. These droplets are caught in the spinning gas stream and are thrown upward towards the wall by centrifugal force. During their motion the, the droplets collide with particles and capture them. The scrubbing liquid along with the particles flows down the wall to the bottom of the scrubber and exits as slurry. The cleaned gas exists through a demister and is processed for the removal of any entrained water droplets.

The collection efficiency for the particles smaller than those recovered in spray towers can be increased through the use of centrifugal scrubbers. Commercial scrubbers have operating efficiency of 97% or better for particles larger than 1 μm .

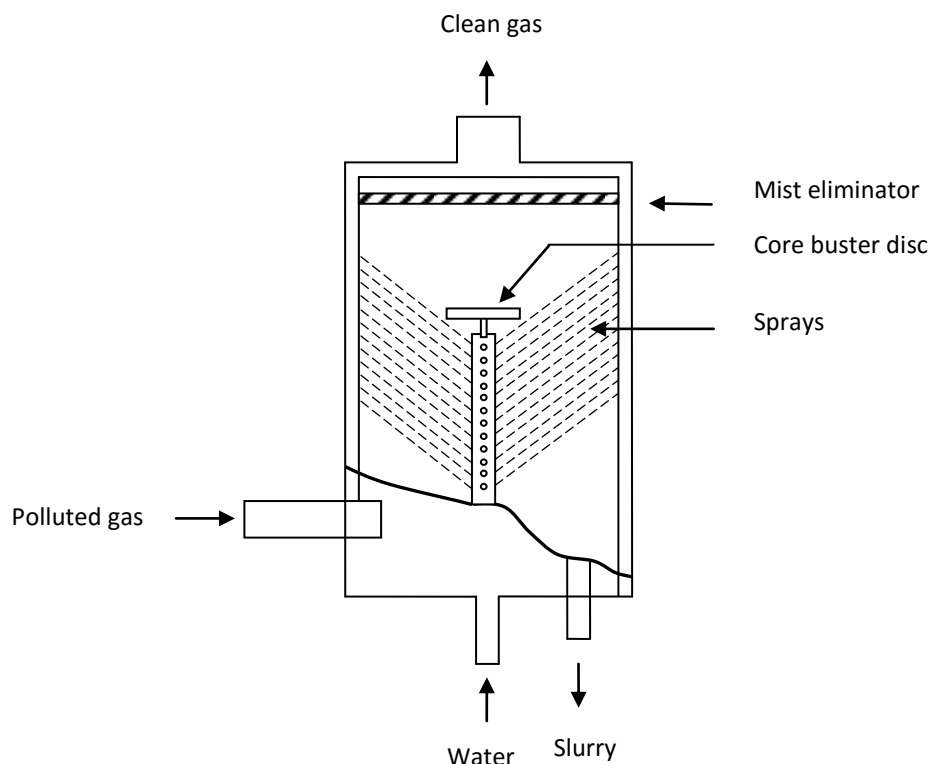


Fig.27. Centrifugal Scrubber, tangential entry

3-Venturi scrubbers

A venturi is a rectangular or circular flow channel which converges to a narrow throat section and diverges back to its original cross section area. The narrow throat causes acceleration of the velocity of the gas to a high level in the venturi section.

Fig.28. shows a vertical downward venturi with throat injection. A bank of nozzles on either side of throat injects water into high velocity gas stream. The high velocity gas assist in atomizing the liquid injected into the gas. The drops collide with dust particles in the gas to form dust-water agglomerates. The gas-liquid mixture is then directed to a separation device such as cyclone separator where the droplets carrying the particulates are separated from the gas stream. Venturi scrubbers offer high performance collection of fine particles usually smaller than 2 to 3 μm . They are suitable when the particulate matter is sticky, flammable or highly corrosive.

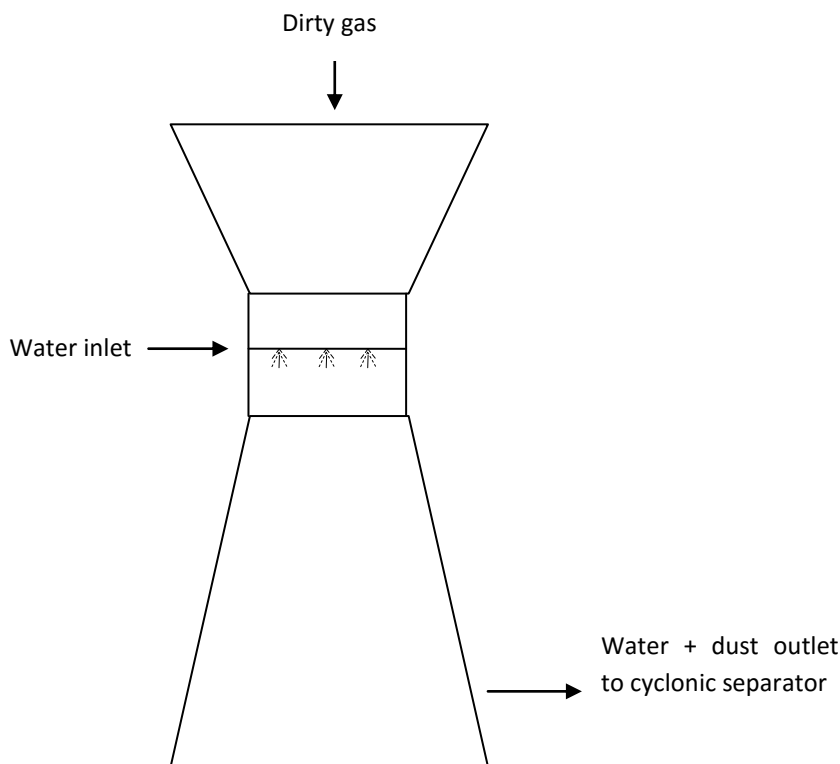


Fig.28. Vertical downward venturi scrubber with throat injection

Air pollution equipment design

Collection efficiency

The collection efficiency measures the system performance. This expressed as a percentage

$$\eta_T = 100 \times \frac{\text{weight.of .material.collected}}{\text{Total.amount.enterin.collector}}$$

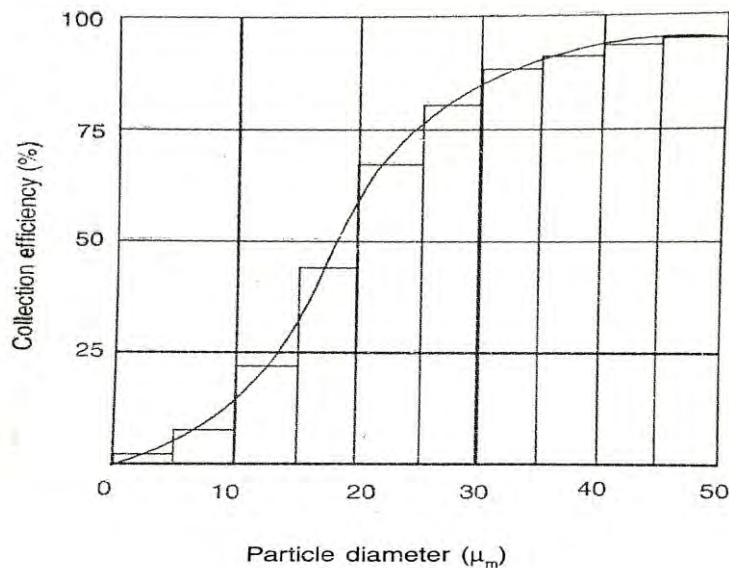


Fig.29. Fractional efficiency curve

where m_i – amount in range “i” entering the collector.

The collection efficiency in each size range can be computed by the equation,

$$\eta_i = \frac{\text{fraction.in.range."i".collected}}{m_i} \times 100$$

The overall collection efficiency η_T can be calculated over n number of size Fractions as:

$$\eta_T = \frac{\sum_{i=1}^n m_i \eta_i}{M} \quad (1)$$

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where M = total amount entering the collector.

Example 1

The following table shows the size distribution of dust sample and the fraction efficiency of removal in a gas cleaning equipment. Calculate the overall collection efficiency.

Dust size	Weight per 100 g of dust (g)	Fractional efficiency η_i (%)
< 5	2	1
5-10	2	7
10-15	4	16
15-20	7	44
20-25	10	67
25-30	8	81
30-35	7	88
35-40	10	92
40-50	15	93
50-60	20	95
60-70	10	98
>70	5	100

Answer

Using Eq.1 we can calculate the overall collection efficiency η_T as

$$\eta_T = \frac{\sum_{i=1}^n m_i \eta_i}{M} = \sum_{i=1}^n w_i \eta_i \quad (1)$$

where $w_i = \frac{m_i}{M}$, the weight fraction in each size. Then the following we get

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Dust size	Weight per 100 g of dust (g)	Weight fraction w_i	Fractional efficiency η_i (%)	$w_i \times \eta_i$
< 5	2	0.02	1	(0.02 x1)
5-10	2	0.02	7	(0.02x7)
10-15	4	0.04	16	(0.04x16)
15-20	7	0.07	44	(0.07x44)
20-25	10	0.1	67	(0.1x67)
25-30	8	0.08	81	(0.08x81)
30-35	7	0.07	88	(0.07x88)
35-40	10	0.1	92	(0.1x92)
40-50	15	0.15	93	(0.15x93)
50-60	20	0.2	95	(0.2x95)
60-70	10	0.1	98	(0.1x98)
>70	5	0.05	100	(0.05x100)
				$\eta_T = 80.17$

1. Settling chamber design (gravity settling)

1.1. Terminal settling velocity

A gravity settler is simply a long chamber through which the contaminated gas passes slowly, allowing time for particles to settle by gravity to the bottom. The important parameter is the terminal or settling velocity of the particle, V_t the terminal velocity is defined as the constant downward speed that a particle attains in a direction parallel to the Earth's gravity field.

If the particle is settling in a fluid at its terminal velocity, three forces acting on it: drag, buoyancy, gravity force, as shown in Fig.30. The terminal settling velocity of the particles is found from forces balance as:

$$F_g = F_D + F_B \quad (2)$$

where

$$F_g = \text{gravity force (secondary Newton law)} = m_p g \quad (3)$$

$$F_D = \text{drag force} = F_D = \frac{\rho_g V_t^2 A C_D}{2} \quad (4)$$

$$F_B = \text{buoyancy force} = F_B = m_p \left(\frac{\rho_g}{\rho_p} \right) g \quad (5)$$

$$m_p = \text{mass of particle} = \rho_p V_p$$

$$g = \text{gravitational acceleration, m}^2/\text{s}$$

$$\rho_g = \text{gas density, kg/m}^3$$

$$\rho_p = \text{particle density, kg/m}^3$$

$$C_D = \text{drag coefficient}$$

$$V_t = \text{terminal velocity, m/s}$$

$$A = \text{frontal cross sectional area, m}^2$$

$$V_p = \text{volume of particle, m}^3$$

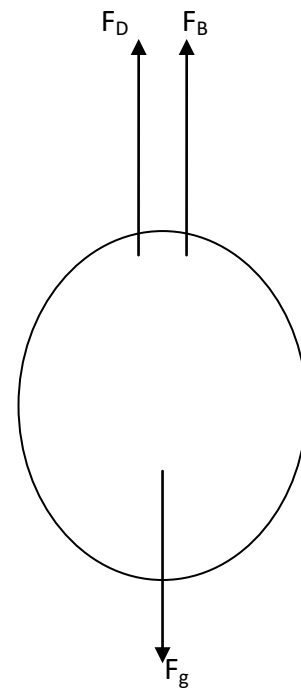


Fig.30 the forces acting on a particle in a fluid

Substituting Eqs. 3,4 and 5 in the overall balance Eq. 2 we get

$$m_p g = \frac{\rho_g V_t^2 A C_D}{2} + m_p \left(\frac{\rho_g}{\rho_p} \right) g \quad (6)$$

The general solution to Eq.6, in term of V_t , is

$$V_t = \sqrt{\frac{2m_p g (\rho_p - \rho_g)}{\rho_p \rho_g A C_D}} \quad (7)$$

for spherical particle

$$V_p = \frac{\pi}{6} d_p^3, \quad A = \frac{\pi}{4} d_p^2, \quad m = \rho_p V_p$$

where d_p = particle diameter, m. substituting the value of V_p and A in the above equation of V_t , we get

$$V_t = \sqrt{\frac{4g d_p (\rho_p - \rho_g)}{3C_D \rho_g}} \quad (8)$$

Eq.8 is the general equation for the terminal settling velocity

where C_D is the drag coefficient which is related to the particles Reynolds number,

$$\text{Where} \quad \text{Re}_p = \frac{\rho_g V_t d_p}{\mu_g} \quad (9)$$

The general drag coefficient for spherical particles may be represented by three relationships.

❖ **In Stocks law region**, laminar flow around the particle

$$C_D = \frac{24}{\text{Re}_p} \quad \text{for } \text{Re}_p < 0.1 \quad (10)$$

- ❖ **In transition region, ($0.1 < Re < 1000$)** this region between the Stokes law region and turbulent region

$$C_D = \frac{18.5}{Re_p^{0.6}} \quad \text{for } 0.1 \leq Re_p \leq 1000 \quad (11)$$

- ❖ **In the turbulent region, ($Re_p < 1000$),** the drag force becomes almost constant with the value of 0.45,

$$C_D = 0.45 \quad \text{for } Re > 1000 \quad (12)$$

The drag coefficient can be calculating within the required range of Reynolds number and then substituted in the Eq(8) to determine the terminal velocity as:

1. Substituting Eqs.9 and 10 into Eq.8, we can calculate the terminal settling velocity in the Stokes region:

$$V_t = \frac{gd_p^2(\rho_p - \rho_g)}{18\mu_g} \quad (13)$$

2. Substituting Eqs.9 and 11 into Eq.8 we can calculate the terminal settling velocity In the transition region.

$$V_t = 0.153 \frac{g^{0.71} d_p^{1.14} (\rho_p - \rho_g)^{0.71}}{\rho_g^{0.29} \mu_g^{0.43}} \quad (14)$$

3. Substituting Eqs.9 and 12 into Eq.8 , we can calculate the terminal settling velocity in the turbulent region:

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$$V_t = 1.73 \left[\frac{g d_p (\rho_p - \rho_g)}{\rho_g} \right]^{1/2} \quad (15)$$

It is difficult to estimate Reynolds number and then to estimate which C_D correlation used to calculate terminal velocity, V_t , because V_t is presented in Reynolds number and C_D equations. Therefore the following equation is used to provide a convenient correlation using K , as

$$K = d_p \left[\frac{g(\rho_p - \rho_g)\rho_g}{\mu_g^2} \right]^{1/3} \quad (16)$$

If the size of particles is known, K value can be calculated from Eq.8:

If $K < 3.3$ then Stokes region applied to estimate V_t , Eq.13.

If $3.3 \leq K \leq 43.6$ then transition region applied to estimate V_t , Eq.14.

If $K \text{ value} > 43.6$ then turbulent region applied to estimate V_t , Eq.15

Example 2

Three different fly ash particles settled through air, their sizes are 0.4, 40, 400 μm . calculate the terminal settling velocity for each particle assume the particle are spherical. Data required given below:

$T_{\text{air}} = 114.5^\circ\text{C}$, $P_{\text{air}} = 1 \text{ atm}$, $\mu_{\text{air}} = 0.021 \text{ cp}$, sp.gr. of fly ash = 2.31

Note: Use K -value as a guide for the region.

Answer

$$K = d_p \left[\frac{g(\rho_p - \rho_g)\rho_g}{\mu_g^2} \right]^{1/3} \quad (16)$$

the gas is air. The density of gas

$$\rho_g = \frac{P.MWt}{RT}$$

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Gas constant $R = 0.082 \frac{atm.m^3}{kgmol.K}$, $T_{air} = 114.5 + 273 = 387.5K$, then the air density

$$\rho_g = \frac{(1)(29)}{(0.082)(387.5)} = 0.9126 kg / m^3$$

The viscosity of air

$$\mu_g = 0.021 cp = 0.021 \times 10^{-3} kg / m.s$$

The density of fly ash = ρ_p

$$\rho_p = sp.gr \times \rho_{H_2O} = 2.31 \times 1000 = 2310 kg / m^3$$

$$K = d_p \left[\frac{9.81(2310 - 0.9126)(0.9126)}{(0.21 \times 10^{-3})^2} \right]^{1/3}$$

$$K = 36056.5 d_p \quad (a)$$

For $d_p = 0.4 \mu m = 0.4 \times 10^{-6} m$

$$K = 36056.5(0.4 \times 10^{-3}) = 0.014$$

$K < 3.3$ then use stocks region for calculating the settling velocity Eq.13

$$V_t = \frac{9.81(0.4 \times 10^{-6})(2310 - 0.9126)}{18(0.21 \times 10^{-3})} = 9.58 \times 10^{-6} m / s$$

For the other particle diameter (40 and 400 μm) are illustrated in the following table

Particle Size μm	K	Region	V_t m/s
0.4	0.014	Stocks	9.58×10^{-6}
40	1.442	Stocks	0.0958
400	14.423	Transition	26.72

1.2. Retention time, τ

Additional parameter in design of settling chamber hydrodynamic is retention time, τ , where

$$\tau = \frac{V}{Q} = \frac{L * W * H}{W * H * u} = \frac{L}{u} \quad (17)$$

where

V = the volume of the settling chamber, m^3

Q = the volumetric flow of gas stream, m^3/s

u = linear gas velocity, m/s

L, W, H = chamber length, width, and height respectively, m

1.3. Chamber efficiency, η

$$\eta = \frac{V_t L}{H u} \quad \text{or} \quad \eta = \frac{V_t W L}{Q} \quad (18)$$

For most air pollution applications, Stock's law Eq.13 is appropriate substituting in Eq.10 as

$$\eta = \frac{d_p^2 g (\rho_p - \rho_g) L}{18 \mu_g H u} \quad (19)$$

With 100% efficiency ($\eta = 1$), Eq.19 becomes

$$d_{p,\min} = \sqrt{\frac{18 \mu_g H u}{g (\rho_p - \rho_g) L}} \quad (20)$$

or

$$d_{p,\min} = \sqrt{\frac{18 \mu_g Q}{g (\rho_p - \rho_g) W L}} \quad (21)$$

Eq.20 & 21 is to determine the minimum particle size $d_{p,\min}$ can removed with 100% efficiency (completely removed).

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Example 3

A hydraulic acid mist in air at 25 °C is to be collected in a gravity settling chamber. Calculate the smallest mist droplet that will be collected by the chamber, applying stock's law. The operating data and dimension of settler are given below:

Wide (W) = 30 ft, Height (H) = 20 ft, Length (L) = 50 ft, $Q_{\text{gas}} = 50 \text{ ft}^3/\text{s}$, $\rho_g = 0.076 \text{ lb/ft}^3$, $\mu_g = 1.24 \times 10^{-5} \text{ lb/ft.s}$, sp.gr of acid mist = 1.6

Answer

$$d_{p,\min} = \sqrt{\frac{18\mu_g H u}{g(\rho_p - \rho_g)L}} \quad (20)$$

$$\rho_p = \text{sp.gr} \times \rho_{H_2O} = 1.6 \times 62.4 = 99.84 \text{ lb/ft}^3$$

$$u = \frac{Q}{A} = \frac{Q}{HW} = \frac{50}{(20)(30)} = 0.083 \text{ ft/s}$$

$$\begin{aligned} d_{p,\min} &= \sqrt{\frac{18(1.24 \times 10^{-5})(20)(0.083)}{32.2(99 - 0.076)(50)}} \\ &= 4.81 \times 10^{-5} \text{ ft} \left(\frac{0.3048 \text{ m}}{1 \text{ ft}} \right) \left(\frac{10^6 \mu\text{m}}{1 \text{ m}} \right) \\ &= 14.7 \mu\text{m} \end{aligned}$$

Design of settling chamber

To design a settling chamber the following equations seems to be useful as a guide:

$$WL = \frac{18\mu_g Q}{g\rho_p d_p^2} \quad (22)$$

$$A_c = WH = \frac{Q}{u} \quad (23)$$

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where

A_c = cross sectional area of the settling tank

Q = volumetric flow rate of the gas stream

W = width of settling chamber

H = height of settling chamber

L = Length of settling chamber

u = linear gas velocity, as a design rule of thumb must be below 10 ft/s (30 m/s).

The minimum height of the chamber (H) should be 1 m for cleaning.

Note Eq. 22 estimated from Eq.19 assuming $\eta = 1$ for design purpose

Example 4

Design a gravity settler to remove all the iron particles from a dust laden stream. The particles diameter $d_p = 35 \mu\text{m}$. Use the following data:

Gas is air at ambient condition with characteristics:

$Q_g = 130 \text{ ft}^3/\text{s}$, $u = 10 \text{ ft/s}$, $\rho_g = 0.0775 \text{ lb/ft}^3$, $\mu_g = 1.23 \times 10^{-5} \text{ lb/ft.s}$, $\rho_p = 475.7 \text{ lb/ft}^3$

Answer

The gas density can be neglected compare to the particle density

$$d_p = 35 \mu\text{m} \left(\frac{1\text{m}}{10^6 \mu\text{m}} \right) \left(\frac{1\text{ft}}{0.3048\text{m}} \right) = 11.48 \times 10^{-5} \text{ ft}$$

$$WL = \frac{18\mu_g Q}{g\rho_p d_p^2} = \frac{18(1.23 \times 10^{-5})(130)}{9.81(475.7)(11.48 \times 10^{-5})^2}$$

$$WL = \text{Collection Area} = 142.5 \text{ ft}^2$$

$$Q = u \times \text{Frontal Area} = u * H * W$$

$$HW = \frac{Q}{u} = \frac{130}{10} = 13 \text{ ft}^2$$

The minimum vertical height required for cleaning purpose ($H = 1 \text{ m} = 3.3 \text{ ft}$)

$$\therefore HW = 13 \text{ ft}^2 \Rightarrow W = \frac{13}{H} = \frac{13}{3.3} = 3.94 \text{ ft}$$

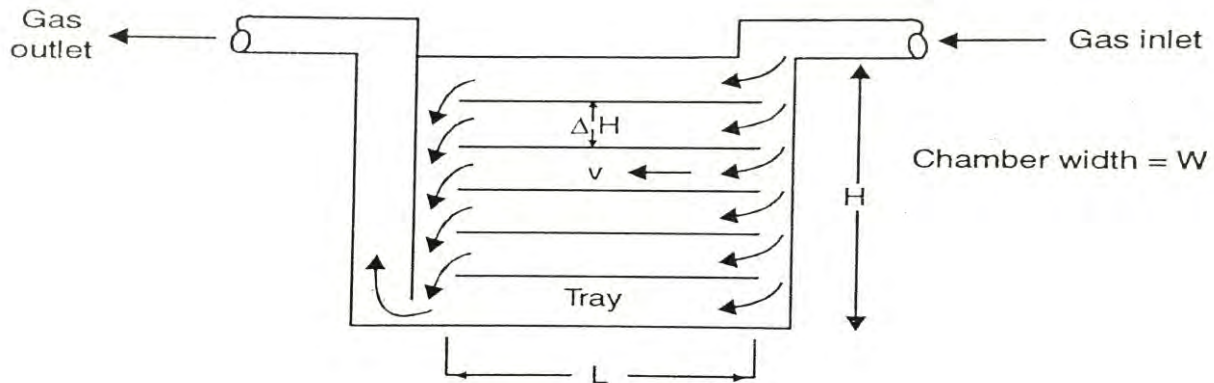
$$\therefore WL = 142.5 \text{ ft}^2 \Rightarrow L = \frac{142.5}{3.94} = 36.2 \text{ ft}$$

$$\begin{aligned} \therefore \text{Total volume of settler} &= WHL \\ &= (3.94)(3.3)(36.2) \\ &= 470.7 \text{ ft}^3 \end{aligned}$$

Design multi-tray Settling chamber

A more elaborate settling chamber is the Howard type whose simplified diagram is shown in Fig.31

Fig.31. Howard settling chamber



For settling chamber having the dimensions $L \times W \times H$ and n number of trays including the bottom surface (Fig.31), the hydraulic diameter for flow passage between the trays is given by

$$D_h = \frac{2W\Delta H}{W + \Delta H} \quad (24)$$

and the Reynolds number,

$$\text{Re} = \frac{v D_h \rho_g}{\mu_g} \quad (25)$$

$$v = \frac{Q}{n W \Delta H}$$

where Q = volumetric flow rate of the gas stream

Substituting for v and D_h in the Eq.25, we get

$$\text{Re} = \frac{2Q\rho_g}{n\mu_g(W + \Delta H)} \quad (26)$$

The spacing between the trays is, ΔH is given by

$$\Delta H = \frac{H}{n}$$

Provided there is no dust layer initially present on the tray surface. Substituting for ΔH in Eq.26 we have

$$\text{Re} = \frac{2Q\rho_g}{\mu_g(nW + H)} \quad (27)$$

The efficiency of collection

$$\eta = \frac{V_t n W L}{Q} \quad (28)$$

and the minimum particle size that can removed 100% efficiency can be found from the equation,

$$d_{p,\min} = \sqrt{\frac{18\mu_g Q}{n W L g(\rho_p - \rho_g)}} \quad (29)$$

Note: previous equations assuming the laminar flow

Example 5

A multi-tray settling chamber having 8 trays. Including the bottom surface, handles 6 m³/s of air at 20 °C. The trays are spaced 0.25 m apart and the chamber is to be 1 m wide and 4 m long.

1. What is the minimum particle size of density 2000 kg/m³ that can be collected with 100% efficiency?
2. What will be the efficiency of the settling chamber if 50 μm particles are to be removed?

Assume Laminar flow condition within the chamber.

μ_g at 20 °C = 1.81×10^{-5} kg/m.s, $\rho_p = 2000$ kg/m³.

Answer

From Eq.29

$$d_{p,\min} = \sqrt{\frac{18\mu_g Q}{nWLg(\rho_p - \rho_g)}}$$

Since the $\rho_p \gg \rho_g$, ρ_g may be neglected in the above equation.

$$d_{p,\min} = \sqrt{\frac{18(1.81 \times 10^{-5})6}{8(1)(4)(9.81)(2000)}} = 5.6 \times 10^{-5} \text{ m} = 56 \mu\text{m}$$

From Eq.28 and using Stock's law for V_t

$$\eta = \frac{V_t nWL}{Q} = \frac{gd_p^2(\rho_p - \rho_g)nWL}{18\mu_g Q}$$

$\eta_{100} = 1$, then the efficiency to remove 50 μm is:

$$\frac{\eta}{\eta_{100}} = \left(\frac{d_p}{d_{p,\min}} \right)^2$$

$$\frac{\eta}{1} = \left(\frac{50}{56} \right)^2 = 80\%$$

Turbulent Flow model (well-mixed settling)

This model is often referred as the well-mixed settling model.

Assume that the gas flow is totally mixed in y-direction and not in x-direction

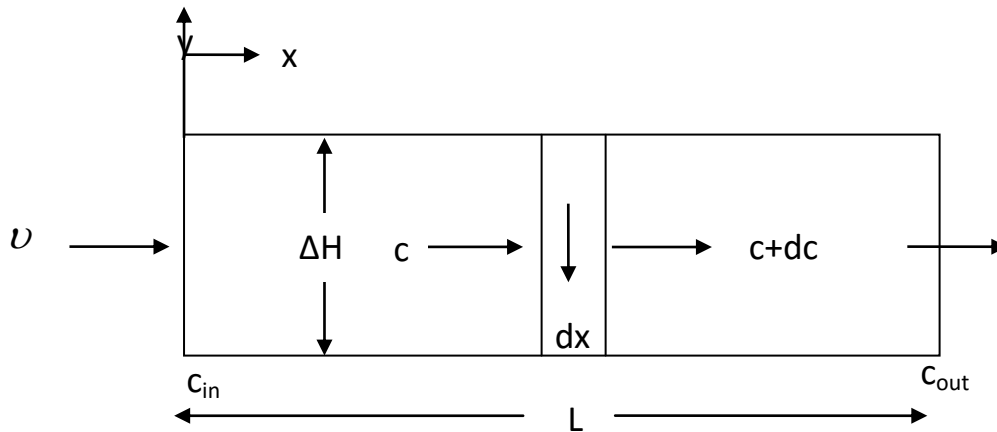


Fig.32. Gravity settling in a horizontal duct: turbulent flow

$$\left\{ \begin{array}{l} \text{Mass concentration of} \\ \text{particles entering the} \\ \text{elemental volum (} Adx \text{)} \end{array} \right\} = \left\{ \begin{array}{l} \text{Mass concentration of} \\ \text{particles leaving the} \\ \text{elemental volum (} Adx \text{)} \end{array} \right\} + \left\{ \begin{array}{l} \text{Mass concentration of} \\ \text{particles leaving the} \\ \text{elemental volum (} Adx \text{)} \end{array} \right\}$$

where c = mass concentration of the particles, and $A = W\Delta H$

$$\int_{c_{in}}^{c_{out}} \frac{dc}{c} = \frac{v_t W}{A v} \int_0^L dx$$

$$\ln \frac{c_{out}}{c_{in}} = \frac{v_t W L}{A v} \quad (31)$$

$$\text{The efficiency} \quad \eta = 1 - \frac{c_{out}}{c_{in}} \quad (32)$$

Substituting Eq.31 into Eq.32 we get the efficiency in term of volumetric flow rate,

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The efficiency $\eta = 1 - \exp\left[-\frac{nWLv_t}{Q}\right]$ (32)

Noting that the term in the bracket is the negative of the efficiency term for the laminar flow (Eq.28), we can write as:

$$\eta_{turb} = 1 - \exp(-\eta_{lami}) \quad (32)$$

Example 6

In example 5, is the laminar flow assumption justified? If not, what is the collection efficiency for 56 and 50 μm particles?

answer

The Reynolds number calculated using Eq.27 as:

$$\text{Re} = \frac{2Q\rho_g}{\mu_g(nW + H)} \quad (27)$$

The kinematic viscosity of air at 20 °C, is $1.51 \times 10^{-5} \text{ m}^2/\text{s}$.

where The kinematic viscosity = $\frac{\mu_g}{\rho_g} = 1.51 \times 10^{-5} \text{ m}^2 / \text{s}$, and $H = 2 \text{ m}$, then:

$$\begin{aligned} \text{Re} &= \frac{2Q\rho_g}{\mu_g(nW + H)} \\ &= \frac{2Q}{\left(\frac{\mu_g}{\rho_g}\right)(nW + H)} \\ &= \frac{2(6)}{1.51 \times 10^{-5}(8 \times 1 + 2)} = 79470 \end{aligned}$$

The flow is turbulent and the laminar flow assumption in example 5 was not justified. Hence, using Eq.32 we get:

$$\eta = 1 - \exp\left[-\frac{nWLv_t}{Q}\right] \quad (32)$$

The terminal velocity using stock's law Eq.13:

$$V_t = \frac{gd_p^2(\rho_p - \rho_g)}{18\mu_g} \quad (13)$$

The dynamic viscosity of air $\mu_g = 1.81 \times 10^{-5}$ kg/m.s

$$\eta = 1 - \exp\left[-\frac{(8 \times 1 \times 4)v_t}{6}\right]$$

The terminal velocity:

$$V_t = \frac{9.8 \times 2000 \times d_p^2}{18(1.81 \times 10^{-5})}$$

$d_p, \mu\text{m}$	$V_t, \text{m/s}$	η
50	0.15	0.55 or 55%
56	0.188	0.63 r 66%

2. Centrifugal separators (Cyclone separators)design

2.1. Cyclone design

Two standard designs for gas-solid cyclones; (a) high-efficiency cyclone, Fig.11a and (b) high gas flow rate cyclone, Fig.12b. The performance curves for the high efficiency cyclone and high gas rate cyclone are shown in Fig.33 a and b these curves can be transformed to other cyclone sizes and operating conditions by use the following scaling equation for a given separating efficiency:

$$d_2 = d_1 \left[\left(\frac{D_{C2}}{D_{C1}} \right)^3 \times \frac{Q_1}{Q_2} \times \frac{\Delta\rho_1}{\Delta\rho_2} \times \frac{\mu_2}{\mu_1} \right] \quad (14)$$

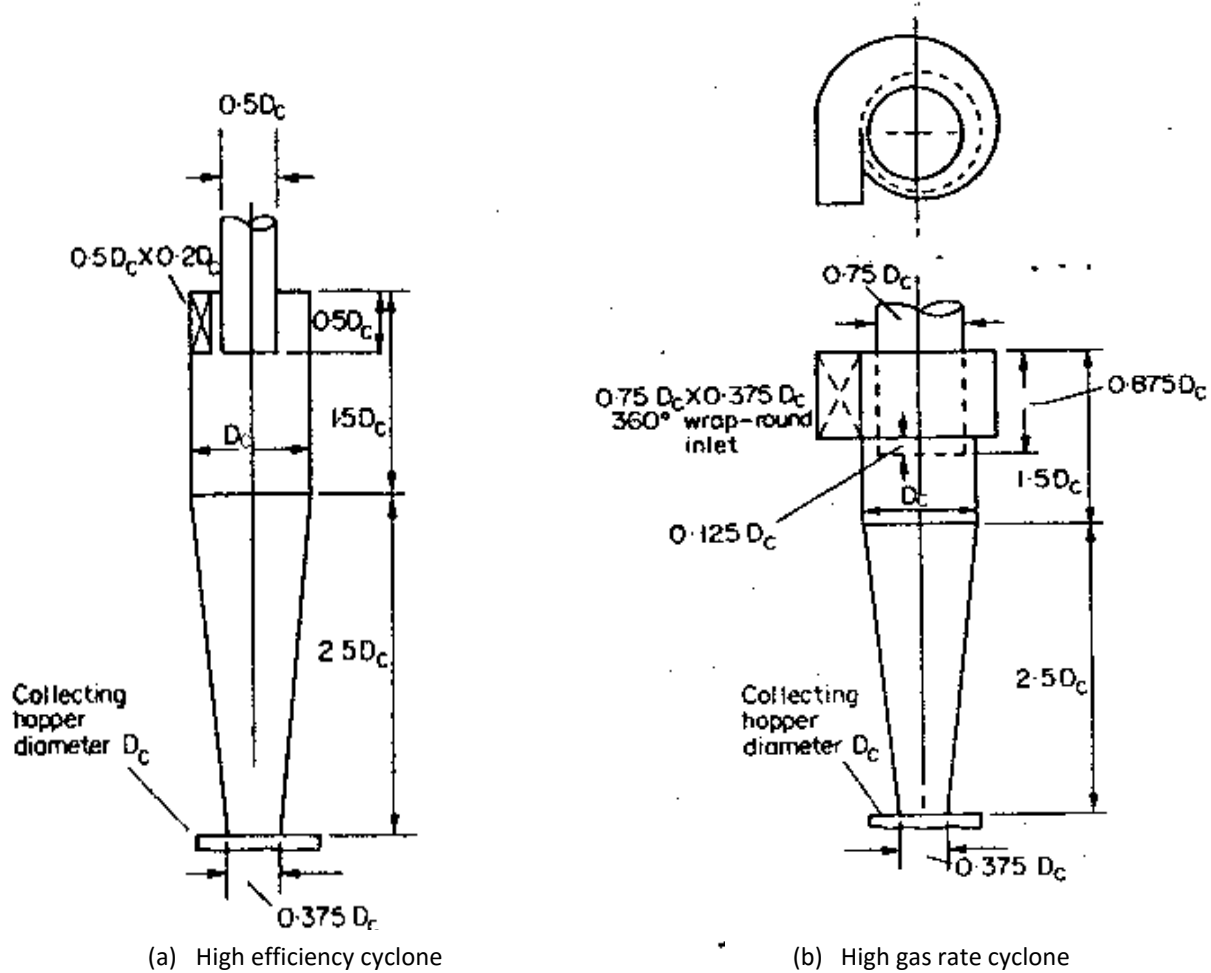
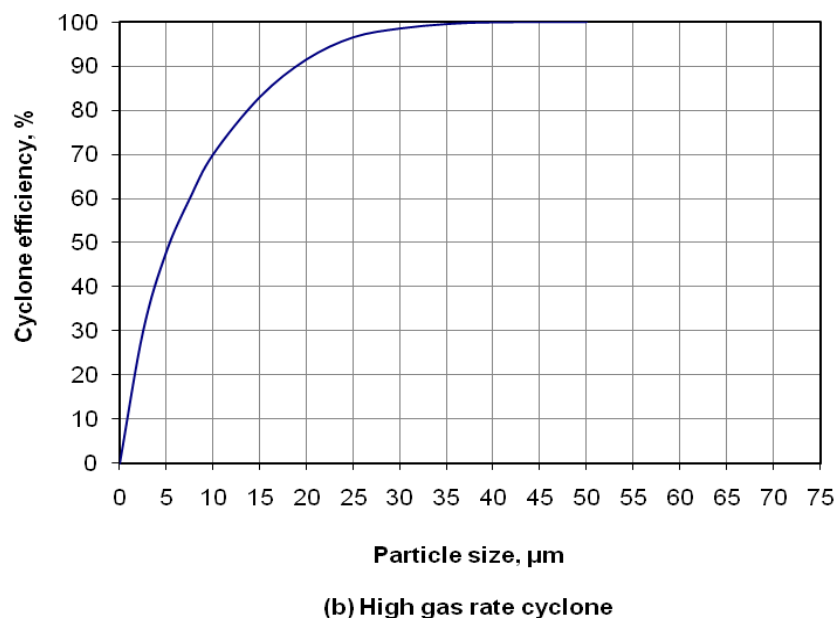
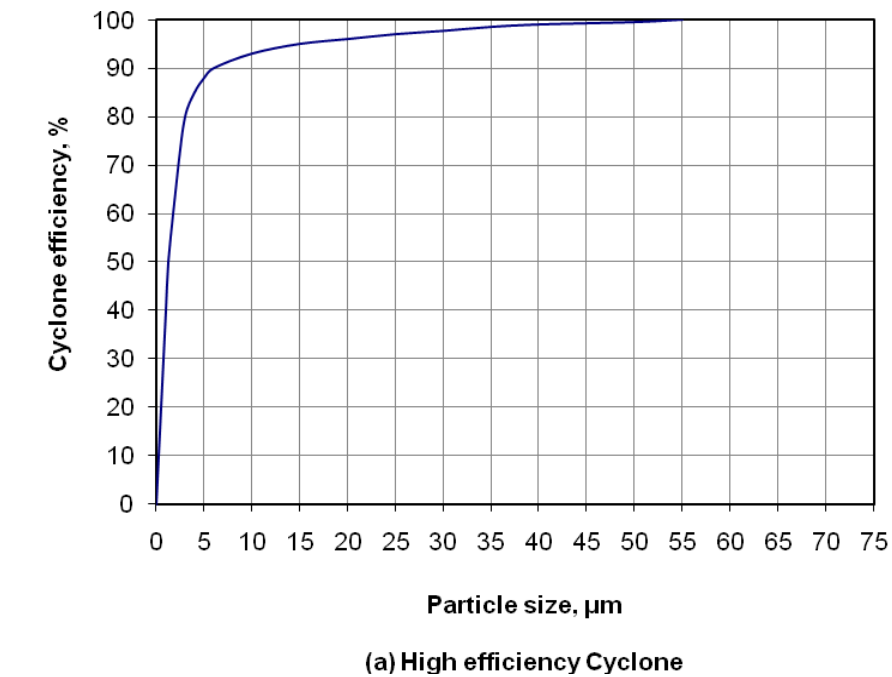


Fig.33. Standard cyclone dimension

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**Fig.34.** Performance curves, standard conditions

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where

d_1 = mean diameter of particle separated at standard condition, at chosen separation efficiency, Fig.13.

d_2 = mean diameter of particle separated in proposed design, at the same separation efficiency.

D_{C1} = diameter of standard cyclone = 8 inches (203 mm).

D_{C2} =diameter proposed cyclone, mm

Q_1 = standard flow rate, m³/h.

for high efficiency design = 223 m³/h.

for high throughput design = 669 m³/h.

Q_2 = proposed flow rate, m³/h.

$\Delta\rho_1$ = solid-fluid density difference in standard condition = 2000 kg/m³.

$\Delta\rho_2$ = solid-fluid density difference, proposed design.

μ_1 = fluid viscosity (air at 1 atm, 20 °C = 0.018 mNs/m²).

μ_2 = fluid viscosity, proposed design.

Hint

*Cyclones should be designed to give an inlet velocity of between 9 and 27 m/s (30-90 ft/s).
The optimum velocity has been found to be 15 m/s (50 ft/s).*

2.2. Cyclone pressure drop

the pressure drop in cyclone will be due to the entry and exit losses, and friction and kinetic energy losses in the cyclone. The empirical equation can be used to estimate the pressure drop:

$$\Delta p = \frac{\rho_g}{203} \left\{ u_1^2 \left[1 + 2\phi^2 \left(\frac{2r_t}{r_e} - 1 \right) + 2u_2^2 \right] \right\} \quad (14)$$

where

Δp = cyclone pressure drop, millibars.

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ρ_g = gas density, kg/m^3 .

u_1 = inlet duct velocity, m/s .

u_2 = exit duct velocity, m/s .

r_t = radius of circle to which the center line of the inlet is tangential, m

r_e = radius of exit pipe, m

ϕ = fraction from Fig.13.

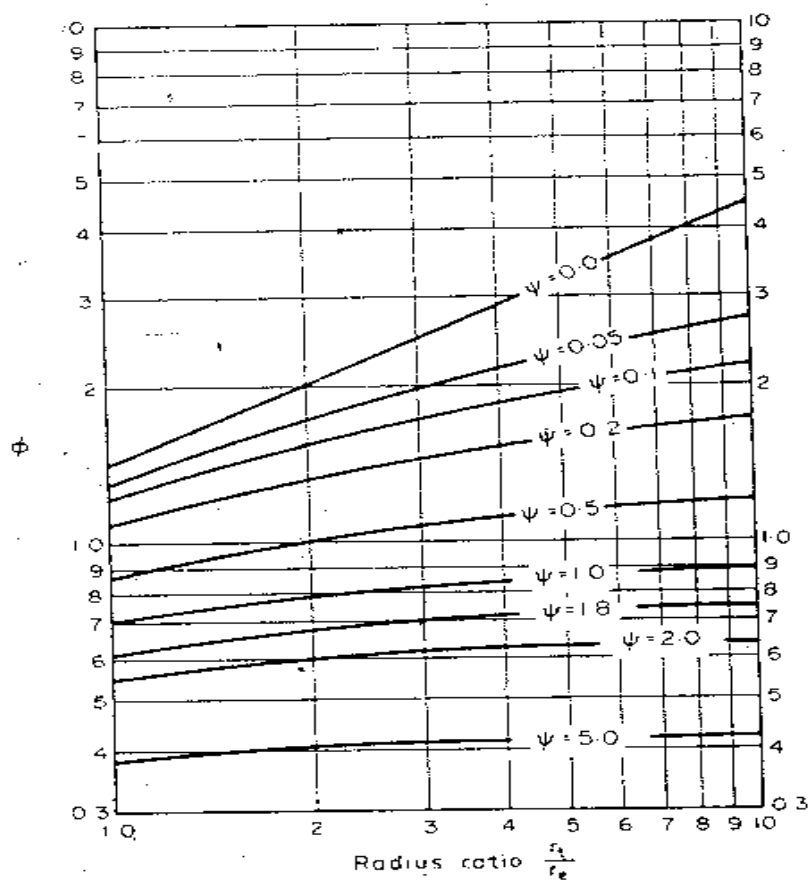


Fig.35. Cyclone pressure drop factor

Ψ = parameter in Fig.14..

$$\psi = f_c \frac{A_s}{A_1}$$

where

f_C = fraction factor, taken as 0.005 for gas.

A_S = surface area of cyclone expose to the spinning fluid, m^2 .

For design purpose this can be taken as equal to the surface area of a cylinder with the same diameter as the cyclone.

A_1 = area of inlet duct, m^2 .

2.3. Cyclone efficiency

The efficiency of cyclone can be estimated by using the concept of a cut diameter, cut diameter can be defined as the particle diameter at which 50% of particle are removed by cyclone:

$$d_{p_{50}} = \left[\frac{9\mu_g b}{2\pi N V_g (\rho_p - \rho_g)} \right]^{1/2} \quad (15)$$

where

μ_g = gas viscosity, kg/m.s.

b = cyclone inlet width, m.

N = effective number of outer turn in the cyclone (normally about 4).

V_g = inlet gas velocity, m/s.

ρ_p = particle density, , kg/m^3 .

P_g = gas density, kg/m^3 .

The cut diameter can be used to establish the collection efficiency for any other diameter particle, d_p , as shown in Fig.36.

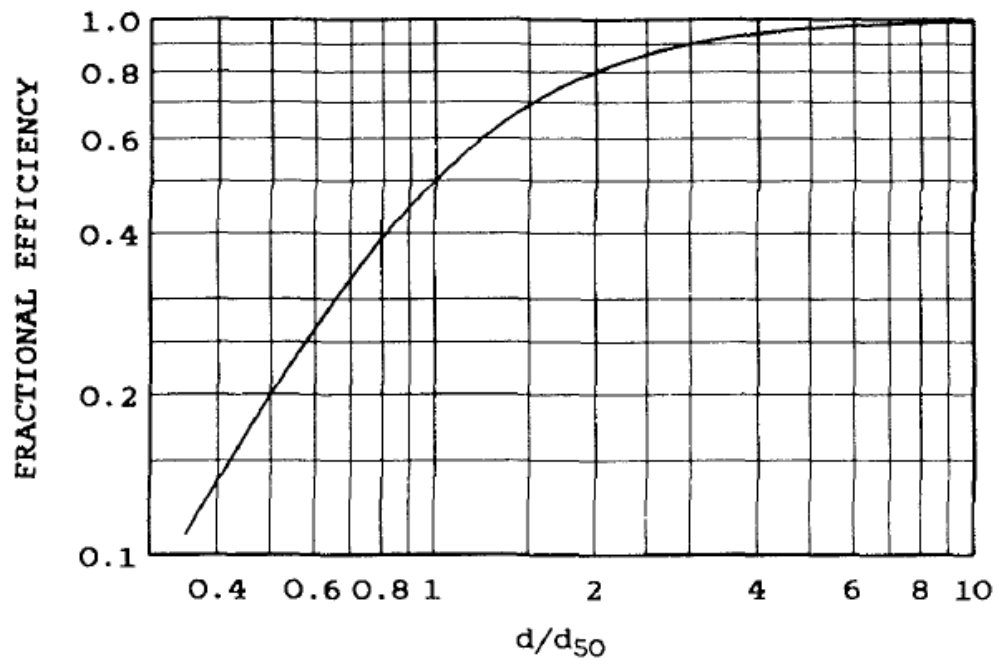


Fig.36. Cyclone efficiency versus particle-size ratio

Solid Waste Management

Solid waste

Solid waste, often called the third pollution, after air and water pollution. Solid waste is that material which arises from various human activities and which is normally discharged as useless or unwanted. It consists:

- Highly heterogeneous mass of discharged materials from the urban community.
- The more homogeneous accumulation of agricultural, industrial and mining waste.

Classification of solid wastes

Solid wastes may be classified based party on content and party on moisture and heating value. A typical classification is as follows:

- Garbage (القمامة المتعفنة):** Refers to the putrescible solid waste constituents (النفايات التي تنتج أثناء إعداد أو تخزين اللحم، الفواكه، الخضراوات، الخ). These wastes have a moisture content of about 70% and heating value of about 6×10^6 J/kg.
- Rubbish (القمامة غير المتعفنة):** Refers to non-putrescible solids waste constituents, either combustible or non-combustible. Combustible wastes would include paper, wood scrap, rubber, leather etc. Non-combustible wastes are metals, glass, ceramics etc. These wastes contain a moisture content of about 25% and heating value of the waste is around 15×10^6 J/kg.
- Pathological wastes (النفايات المرضية):** Dead animals, human waste, etc. The moisture content is 85% and there are 5% non-combustible solids. The heating value is around 2.5×10^6 J/kg.
- Industrial wastes (النفايات الصناعية):** Chemicals, paints, sand, metal ore processing, fly ash, sewage treatment sludge etc.
- Agricultural wastes (النفايات الزراعية):** Farm animal manure (السماد)، crop residues etc.

Solid waste disposal methods

An appropriate selection of disposal method of solid waste can save and avoid future problems. The method should also provide opportunities for recycling of materials if possible, and should not pollute the air, the ground water, the surface water or the land. Several disposal methods are being used in the various parts of the world and the most prominent of these are:

1. Open dumping (الرد على عيش وطيء)
2. Sanitary landfill (الطمر الصحي)
3. Incineration (الحرق)
4. Composting (التسميد)

1. Open dumping

Open dumping is practiced in many cities because it is cheap and requires no planning. The open dumps cause public health problems by encouraging the breeding of flies, rats, mosquitoes and other pests. They also become source of objectionable odors and cause air pollution when the wastes are burned in order to reduce their volume and conserve space.

2. Sanitary landfill

Sanitary landfilling is an engineering operation, designed and operated according to acceptable standards. It may be defined as a method of disposing refuse on land without creating nuisances or hazards to public health or safety.

In sanitary landfill operation, refuse is spread and compacted in thin layers within a small area. This layered structure is usually referred to as a cell. To allow for proper compaction, the cell depth should not exceed about 2 meters. The cell is then covered with a layer of soil which is spread uniformly and then compacted. To provide an adequate seal the cover should normally be at least 20 cm thick. When a number of cells reach the final desired elevation, a final cover of about one meter of earth is placed and it is again compacted. The final cover is necessary to prevent rodents (اللقوارض) from burrowing (الاغباء) into refuse.

3. Incineration

Incineration involves burning of solid wastes at high temperature, leftover ashes, glass, metals and unburned combustible amount to perhaps 25% of the original waste. Incineration leads to air pollution unless the plant is designed, equipped and operated to comply with air pollution standards. Typical air pollution from incineration is fly ash, SO₂, hydrogen chloride, and organic acid. Incineration is an economic method for solid waste disposal because useful material and energy can be recovered from the process. Heat can be recovered by putting a waste heat boiler or some other recovery device on an

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existing waste incinerator. The solid waste has about one-third the heating value of coal with very low sulfur content.

The advantages of incineration include a wide range ability for handling varying loads and small space requirement for ultimate disposal. However, the method requires fairly high level of maintenance and the operating costs are higher than those for operating of a sanitary landfill.

4. Composting

Composting of refuse is an aerobic method of decomposing solid waste. Many types of microorganisms already present in the waste stabilize the organic matter in the waste to produce a soil conditioner.

Initially, the process starts with the mesophilic bacteria which oxidize the organic matter in the refuse to carbon dioxide and liberate heat. The temperature rise to about 45 °C and at this point the thermophilic bacteria take over and continue to decomposition. During this phase, the temperature further rise to about 60 °C . The refuse is periodically turned over to allow sufficient oxygen to penetrate to all parts of the material to support aerobic life. After about three week, the compost is stabilized. The end point of operation can be measured by noting a drop in temperature. The compost should have an earthy smell and a dark brown color.

Safety

Safety, Health, and Environmental 5%

- A. Hazardous properties of materials (e.g., corrosive, flammable, toxic), including MSDS
- B. Industrial hygiene (e.g., noise, PPE, ergonomics)
- C. Process hazard analysis (e.g., using fault-tree analysis or event tree)
- D. Overpressure and underpressure protection (e.g., relief, redundant control, intrinsically safe)
- E. Storage and handling (e.g., inerting, spill containment)
- F. Waste minimization
- G. Waste treatment (e.g., air, water, solids)

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